# DEVELOPMENT OF COLOUR-MARK SENSOR-BASED CALIBRATION SYSTEM FOR TIMING DEVICES WITH SEVEN-SEGMENT LIQUID-CRYSTAL-DISPLAY

AHMAD SAHAR BIN OMAR

UNIVERSITI TEKNOLOGI MALAYSIA

# DEVELOPMENT OF COLOUR-MARK SENSOR-BASED CALIBRATION SYSTEM FOR TIMING DEVICES WITH SEVEN-SEGMENT LIQUID-CRYSTAL-DISPLAY

AHMAD SAHAR BIN OMAR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JUNE 2015

*To my beloved wife and children*
*who are always there for me*

*Noor Ruzilawati binti Mohd Nor*
*Ahmad Haziq Mirza bin Ahmad Sahar*
*Ahmad Rafiq Iman bin Ahmad Sahar*

*To my beloved family*

*Allahyarham Omar bin Harun*
*Azinah binti Yaakob*
*Siti Salina binti Omar*
*Siti Shariza binti Omar*
*Siti Salome binti Omar*

*You are always on my mind...*

## ACKNOWLEDGEMENT

I wish to express my sincere gratitude to my supervisor, Dr. Mohd. Fauzi bin Othman for his encouragement, guidance, criticism and friendship. I also extend my special thanks and appreciation to Dr. Mohd. Nasir Zainal Abidin and Mr. Erik Dierikx for their technical support and expertise.

I am also indebted to the Ministry of Science, Technology and Innovation of Malaysia and SIRIM Berhad for the scholarship and fund provided in developing the prototype calibration system.

My fellow colleagues should also be recognized for their support and assistance in various occasions. Their views and opinions are indeed useful.

And last but not least, special thanks go to all of my family members who have given me strength and moral support in completing this thesis.

## ABSTRACT

There is a need for a better calibration system of timing devices at the National Metrology Laboratory, SIRIM Berhad (NML-SIRIM), particularly stopwatches and timers with seven-segment LCD. This research is focused on the development of a prototype calibration system which is based on the idea of utilizing a colour-mark sensor. It comprises of the process of predefining key specifications, designing a new calibration method, constructing a prototype measuring instrument and performing an experimentation test and finally carrying out an evaluation performance test via bilateral comparison with the existing calibration system of NML-SIRIM and also with the National Measurement Institute of Netherlands (VSL). To the best of the author's knowledge, there are as yet no reference publications or reports of calibration system involving the use of colour-mark sensor for the calibration of timing devices. Based on the observation and data analysis of the conducted experimentation tests, it shows that the developed prototype or so called the colour-mark sensor based calibration system can operate regardless of the intensity of ambient light and the measurement uncertainty is not constrained either by human reaction time or by resolution of the timing device being tested. Instead it is limited by the sensor reaction time and the counting capabilities of the prototype calibration system. There is also no need to dismantle the casing of the timing device under test in performing the calibration. Furthermore, the functionality of the timing device under test in counting the time can also be tested. The results from bilateral comparison show that the best measurement uncertainty of this prototype calibration system is ± 0.016 seconds per day, which is comparable to the best existing calibration method mentioned in this thesis.

# ABSTRAK

Suatu sistem tentukuran alat pengukur masa yang lebih baik diperlukan di Makmal Metrologi Kebangsaan, SIRIM Berhad (NML-SIRIM) terutamanya untuk jam randik dan pemasa jenis tujuh segmen LCD. Penyelidikan tertumpu kepada pembangunan sistem tentukuran prototaip yang berdasarkan kepada idea menggunakan sensor jenis tanda warna. Ianya merangkumi proses pra penentuan spesifikasi utama, merekacipta kaedah penentukuran baru, membina prototaip alat pengukur dan menjalankan ujian eksperimentasi dan melaksanakan ujian prestasi penilaian melalui perbandingan dua hala dengan sistem tentukuran sedia ada NML-SIRIM dan juga dengan National Measurement Institute of Netherlands. Berdasarkan pengetahuan pengarang, masih belum ada lagi penerbitan rujukan atau laporan sistem penentukuran melibatkan penggunaan sensor tanda warna untuk tujuan tentukuran alat pengukur masa. Berdasarkan pemerhatian dan analisis data ujian eksperimentasi, didapati prototaip yang juga dikenali sebagai sistem tentukuran jenis sensor tanda warna boleh beroperasi tanpa dipengaruhi oleh keamatan cahaya sekeliling dan ketidakpastian pengukurannya tidak dipengaruhi oleh masa tindak balas manusia serta resolusi alat pengukur masa yang ditentukur. Sebaliknya ianya dipengaruhi oleh masa tindak balas sensor tanda warna dan keupayaan pembilang sistem tentukuran prototaip. Alat pengukur masa yang ditentukur juga tidak perlu dibuka. Selain itu, fungsian alat pengukur masa yang ditentukur juga dapat diuji. Keputusan dari perbandingan dua hala telah menunjukkan bahawa ketidakpastian pengukuran terbaik sistem tentukuran prototaip ini adalah ± 0.016 saat per hari, di mana ianya adalah setanding dengan kaedah tentukuran terbaik sedia ada yang telah dinyatakan di dalam di tesis ini.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A_{ctivation}$ | - | Relative intensity level readout of activation of the colour-mark sensor. |
| $a_+$ | - | Upper limit |
| $a_-$ | - | Lower limit |
| $c_i$ | - | Sensitivity coefficient |
| $D_{eactivation}$ | - | Relative intensity level readout of deactivation of the colour-mark sensor |
| $D_{sys}$ | - | Deviation of the prototype calibration system |
| $D_{f_i}$ | | Deviation of the reference frequency input |
| $E_n$ | - | $E_n$ scores |
| $f_i$ | - | Actual frequency of 1 kHz |
| $f_{measured}$ | - | Measured frequency |
| $f_{nominal}$ | - | Nominal frequency |
| $k$ | - | Coverage factor |
| $n$ | - | Number of measurement |
| $\bar{q}$ | - | Sample mean |
| $q_k$ | - | Result of $k$ th measurement |
| $s$ | - | Standard deviation |
| $T_{nom}$ | - | Nominal time interval |
| $T_{rdo}$ | - | Readout time interval of prototype calibration system |
| $T_{sys}$ | - | Actual time interval readings reported by prototype calibration system |
| U | - | Expanded uncertainty |
| $U_{proto}$ | - | Uncertainty reported by prototype calibration system |

| | | |
|---|---|---|
| $U_{ref}$ | - | Uncertainty reported by NML-SIRIM and VSL calibration system |
| $u_c$ | - | Combined uncertainty |
| $V_{p\text{-}p}$ | - | Peak to peak voltage |
| $v$ | - | Degree of freedom |
| $v_{eff}$ | - | Effective degree of freedom |
| $Y_{proto}$ | - | Time interval reported by prototype calibration system |
| $Y_{ref}$ | - | Time interval reported by NML-SIRIM and VSL calibration system |

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| BIPM | - | International Bureau of Weights and Measures |
| CENAM | - | Centro Nacional de Metrologia |
| CBT | - | Cesium Beam Tube |
| DUT | - | Device Under Test |
| GPIB | - | General Purpose Interface Bus |
| GPS | - | Global Positioning System |
| ISO | - | International Organisation for Standardisation |
| LCD | - | Liquid-crystal Display |
| LSD | - | Least Significant Digit |
| KRISS | - | Korea Research Institute of Standard and Science |
| MNFS | - | Malaysian National Frequency Standards |
| NIST | - | National Institute of Standards and Technology |
| NMI | - | National Metrology Institute |
| NML-SIRIM | - | National Metrology Laboratory, SIRIM Berhad |
| NRC | - | National Research Council |
| NTSC | - | National Time Service Center |
| OIML | - | International Organization of Legal Metrology |
| SCL | - | Hong Kong Standards and Calibration Laboratory |
| SI | - | International System of Units |
| TCXO | - | Temperature Controlled Crystal Oscillator |
| USNO | - | United States Naval Observatory |
| UTC | - | Coordinated Universal Time |
| VCXO | - | Voltage-controlled Crystal Oscillator |
| VIM | - | International Vocabulary of Metrology |
| VSL | - | National Metrology Institute of Netherlands |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Problem

Timing devices, particularly those with a seven-segment LCD are perhaps used every day in industrial and commercial activities, and for almost unlimited number of applications. Thus, it is very important to calibrate, verify and certify these timing devices periodically using an accurate and traceable calibration system, in order to ensure these timing devices are well within the allowable tolerance as stipulated in the national and international legal metrology requirements as well as the technical requirements of ISO 17025.

When a timing device is calibrated by an equipment, the calibrating equipment must be more accurate (has lower measurement uncertainties) than the device that will be calibrated. Otherwise, the measurement results will be invalid. Consecutively, that accurate calibrating equipment must be compared against a more accurate standard. Likewise, that more accurate standard needs to be periodically compared to an even more accurate standard, until eventually a comparison is made against a national or international standard that represents the best physical realization of the SI unit that is being measured, which is the SI second. This series of comparison that goes back to SI unit, is formally known as metrological traceability which sometimes can be illustrated using a pyramid as shown in Figure 1.1 which represents the calibration uncertainties decreasing as it goes up to the SI units. Metrological traceability is defined by international agreement, as:

The property of a measurement result, whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [1]

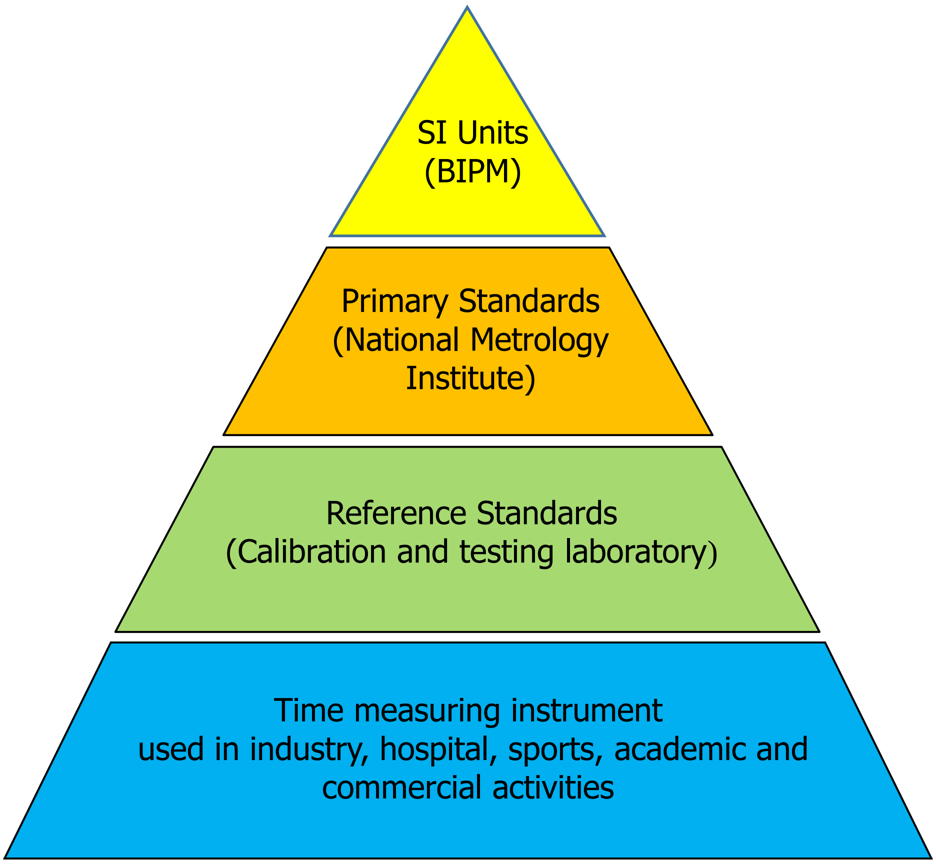


**Figure 1.1** A metrological traceability illustrated as a pyramid

Therefore, it is very important for every national metrology institutes and calibration laboratories to ensure that their measurement standards and calibrating equipment is traceable to the SI unit [2]. Moreover, if a statement of ‘in tolerance’ or ‘out of tolerance’ based on the device’s metrological specification is intended to be made in the calibration report, the measurement uncertainty of the calibration method to be used must be small enough, preferably four times smaller than the allowable tolerance of the device to be verified in order to ensure that the calibration result is valid [3].

The timing devices that will be used for commercial activities such as parking meters, time recorders and taximeters are compulsory to be calibrated, verified and certified. A calibrated stopwatch is often used for field calibration to verify the accuracy of these commercial timing devices [4]. The accuracy of these commercial timing devices must be ‘in tolerance’ with the allowable tolerance before it is permitted to be operated and used to charge the customer. In Malaysia, there are laws such as the National Measurement System Act and Weight and Measures Act that are used for defining and regulating the legal metrology requirements of these commercial timing devices. These laws are intended for fair trading. Other countries, such as the United States also have similar metrological regulations for controlling the accuracy of the operating commercial timing devices [4-6]. For example, a person who pays for 1 hour on parking meter is legally entitled to receive one hour with plus/minus tolerance. Legal metrology does not only protect the consumer but also the seller. Table 1.1 summarizes the acceptance tolerances of the commercial timing devices which correspond to the respective legal metrology requirements in Malaysia and internationally as well.

**Table 1.1**: Summary of legal metrology requirements for commercial timing devices.

| Timing Devices | Time Accuracy / Allowable Tolerance |
|---|---|
| Parking Meter | 3 % [7] |
| Time Recorder | 3 s per hour (0.08 %), but not exceed one minute per day (0.07%) [8] |
| Taximeter | Taximeter not installed in the vehicle: 0.2 s or 0.1 % whichever is greater [9]<br><br>Taximeter installed in the vehicle: 0.2 % [9] |

Other important things that should be highlighted apart from the requirements of the legal metrology, is the necessity to calibrate and verify the timing device in guaranteeing its accuracy is well within the manufacturer's specifications especially during the final acceptance test and factory quality control.

For example: The manufacturer's specifications of stopwatch model Citizen claims that its accuracy is 99.99957 % or 0.00043 % tolerance of error, which it stated in the instruction manual shown in the Appendix.

As has been agreed earlier, it is very important to ensure that the calibration method has the measurement uncertainty that is relatively small when compared to the stopwatch accuracy we are attempting to verify. To illustrate this, assuming that we are calibrating the stopwatch model Citizen using the totalize method (that will be further discussed in Chapter 2) and employing a 4:1 rule formula for acceptable uncertainty. This means that the expanded measurement uncertainty of the calibration method must be four times smaller than the acceptable tolerance of the stopwatch under test in order to declare the unit to be in or out of tolerance to the manufacturer's specification of 0.00043 %. The measurement uncertainty of the totalize method is 38 ms. By using the 4:1 rule formula, the tolerance must be 152 ms in order for measurement uncertainty of totalize method to be one quarter of the tolerance of the stopwatch under test. Therefore, the amount of time required to elapse on the stopwatch per one reading would be at least:

$$\mathbf{\frac{0.152\ s}{0.00043\ \%} = 35348.84\ s\ (approximately\ 9.8\ hours)}$$

Typically in verification, the measurement is repeated for at least three times. Therefore, it requires a total measurement time of approximately 30 hours to complete the verification work. This is lengthy, and the laboratory that verifies it to 0.00043 % would clearly need to consider a more appropriate method with better measurement uncertainties. Thus, the smaller the measurement uncertainty of the method, the faster the calibration and verification work can be completed.

## 1.2 Statement of the Problem

Prior to the start of this research, a survey has been conducted at NML-SIRIM in order to know how many and what type of timing devices are received by NML-SIRIM for calibration services. Based on the information acquired from the calibration services records retained by NML-SIRIM, there were about 415 timing devices including stopwatches, timers and parking meters received between the year 2009 to 2011, and 98% of these timing devices have a seven-segment LCD for displaying its time interval or time of the day. This is perhaps due to the fact that the LCD is widely used especially in battery-operated timing devices such as stopwatches and timers due to their low power consumption [10].

Since 2004, NML-SIRIM has been using the in-house designed stopwatch/timer calibrator to provide calibration services for these timing devices. However, there are some drawbacks of using this calibrator that will be further discussed in Chapter 2. In some cases, NML-SIRIM need to use another calibration method, namely the totalize method and photo totalize method as an alternative solution for the calibration that cannot be performed by the NML-SIRIM's calibrator. These methods were chosen, because of the required equipment used in this method are freely available at the NML-SIRIM. However, there are still some drawbacks of using these methods that will be further discussed in Chapter 2.

Based on the aforementioned information, it is clearly justified that a better calibration system at NML-SIRIM, Malaysia particularly for timing devices with seven-segment LCD is necessary to be developed which could also offer an alternative solution to overcome some drawbacks faced by the existing calibration method.

## 1.3 Objectives of the Study

The main objectives of this study are:

(i) To review the existing calibration method for timing devices with display.

(ii) To propose a new calibration method for timing devices with display.

(ii) To develop a prototype calibration system based on the proposed calibration method.

(iii) To evaluate the performance of the developed prototype calibration system.

## 1.4 Scope of the Study

A new calibration method particularly for timing devices with seven-segment liquid crystal display (LCD) shall be designed and a prototype calibration system shall be constructed to realize this new method into practical by utilizing a colour-mark sensor. The prototype is intended to be used in the laboratory under a controlled environmental condition of (21±2)$^{o}$ C and (60±10) % Relative Humidity.

## 1.5 Significance of the Study

This study proposes a better calibration system at NML-SIRIM, particularly for timing devices with seven-segment LCD. Furthermore, the prototype calibration system to be developed shall be operated based on a new method that can offer an alternative solution over the existing calibration method employed by the National Metrology Institutes. With this development, it certainly contributes to the improvement of calibration services of timing devices primarily in fulfilling the legal and industrial metrology requirements in Malaysia.

## 1.6 Thesis Outline

This thesis is structured as follows. Chapter 1 begins with the introduction of the thesis. Chapter 2 outlines the basic operation of timing devices, metrological concepts and literature review of the existing calibration method of timing devices where the calibration procedure, measurement uncertainty, advantages and disadvantages of each of these methods are summarized. Chapter 3 is the research methodology, where it elaborates on how the prototype colour-mark sensor-based calibration system is designed, constructed and tested. Chapter 4 will discuss the results and findings gained in the research methodology. Finally, Chapter 5 will explain the conclusion and future work that could be undertaken to further improve the prototype of colour-mark based-calibration system.

## REFERENCES


1. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML. *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*. JCGM 200:2012. 2012.

2. International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories*. Switzerland, ISO/IEC Guide 17025. 2005.

3. J. C. Gust, R. M. Graham, and M. A. Lombardi. *Stopwatch and Timer Calibrations*. Special Publication 960-12. United States : National Institute of Standard and Technology. 2009.

4. M. A. Lombardi. Legal and Technical Measurement Requirements for Time and Frequency. *NCSLI Measure : The Journal of Measurement Science*. 2006. 1(3): 60-69.

5. T. Butcher, L. Crown, L. Sebring, R. Suiter, J. Williams. *Specifications, Tolerances, and other Technical Requirements for Weighing and Measuring Devices*. Handbook 44. United States : National Institute of Standard and Technology. 2007.

6. R. J. Anderson and G. L. Harris. *Specifications and Tolerances for Field Standard Stopwatches*. Handbook 105-5. United States : National Institute of Standard and Technology. 1997.

7. Malaysia. *Pattern or Specifications for Weights or Measures or Instruments for Weighing or Measuring (Amendment) Order 1990, Part XVI Parking Meters, Weights and Measures Act 1972*. P.U. (A) 433. 1990.

8. Malaysia. *Pattern or Specifications for Weights or Measures or Instruments for Weighing or Measuring (Amendment) Order 1990, Part XVII Time Recorders Used for Measuring Parking Time, Weights and Measures Act 1972*. P.U. (A) 433. 1990.

9. International Organizaion of Legal Metrology (OIML). *Taximeters : Metrological and Technical Requirements, Test Procedures and Test Report Format*. Paris, OIML R21. 2007

10. Ronald J. Tocci. *Digital System : Principles and Applications*. 6th edition. Englewood Cliffs, New Jersey. : Prentice-Hall. 1995.

11. Robbins, Michael. *Electronic Clocks and Watches*. Howard W. Sams Co., Indianapolis (US). 1975.

12. J. R. Vig. *Introduction to Quartz Frequency Standards*. Army Research and Development Technical Report. SLCET-TR-92-1. 1992.

13. EURAMET. *Metrology-In Short*. 3rd edition. ISBN 978-87-988154-4-7. 2008.

14. International Organizaion of Legal Metrology (OIML). I*nitial and Subsequent Verification of Measuring Instruments and Processes*. Paris, OIML D20. 1988.

15. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML. *Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement*. JCGM 100:2008. 2008.

16. R.M. Graham. Stopwatch Calibration Part I : The Direct Comparison Method. *NCSLI Measure: The Journal of Measurement Science*. 2006. 1(1) : 72-73.

17. Solis, R.F., et al. An Interlaboratory Stopwatch Comparison in the SIM Region. *NCSLI Measure: The Journal of Measurement Science*. 2011. 6(3): 56-62.

18. R.M. Graham. Stopwatch Calibration Part II : The Totalize Method. *NCSLI Measure: The Journal of Measurement Science*. 2006. 1(2) : 72-73.

19. C. M. Tsui, Y. K. Yan, and H. M. Chan. Calibration of Stopwatches by Utilizing High Speed Video Recordings and a Synchronous Counter. *NCSLI Measure: The Journal of Measurement Science*. 2011. 6 (3): 64-71.

20. A. Sahar, M.Nasir, A. Rashid and Md. Nor. Development of the Stopwatch/Timer Calibration System at National Metrology Laboratory, Malaysia. *6th International Conference on Advances in Metrology(AdMet)*. December 11-13, 2006. New Delhi, India : APMP. 2006. 39-43.

21. R.M. Graham. Stopwatch Calibration Part III : The Time Base Method. *NCSLI Measure: The Journal of Measurement Science*. 2006. 1(3) : 74-75.

22. International Association of Athletics Federations (IAAF). *IAAF Calibration and Testing Manual Edition 2010* is located at http://rdcjakarta.org/calibration%20and%20Testing%20Manual%202010.pdf

23. Horský, J., and J. Horská. Stopwatch and Timer Calibrations with Internet Reference Signal. *Системи обробки інформації*. 2013. 3 : 112-115.

24. Barry N. Taylor and Chris E. Kuyatt. *Guideline for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. Technical Note 1297. United States : National Institute of Standard and Technology. 1994.

25. The BIPM KCDB is located at http://kcdb.bipm.org

26. J. Engdahl and H. Matthey. 32 kHz Quartz Crystal Unit for High Precision Wrist Watch. *Proceedings of the 29th Annual Symposium on Frequency Control*. May 28-30, 1975. Atlantic City, N.J : IEEE. 1975. 187-194.

27. Desarzens, Pierre, and Jacques Vogt. *Apparatus for Rapidly Evaluating the Rate of a Timekeeper*. U.S. Patent 3, 857,274. 1974.

28. Greiner, Rudolf. *Method For Measuring the Accuracy of Time-Pieces*. U.S. Patent 3,238,764. 1966.

29. Yanagawa, Yoshihiko, and Shizuo Yamaguchi. *Method of and System for Detecting the Rate of an Electronic Timepiece*. U.S. Patent 3,946,591. 1976.

30. Bichsel, Daniel. *Pickup for Measuring the Rate of an Electronic Timepi*ece. U.S. Patent 4,030,337. 1977.

31. Cho-man Tsui and Hon-man Chan. Circuits for the Calibration of Quartz and Mechnical Testers. *NCSLI Measure: The Journal of Measurement Science.* 2012. 7 (4): 26-27.

32. *Fundamentals of Liquid Crystal Displays – How They Work and What They Do* is located at www.fujitsu.com/downloads/MICRO/fma/pdf/LCD_Backgrounder.pdf

33. G. H. Heilmeier, L. A. Zanoni, and L. A. Barton. Dynamic scattering : A New Electrooptic Effect in Certain Classes of Nematic Liquid Crystals. Pr*oc. IEEE*. 1968. 56:1162-1171.

34. Lechner, B.J.; Marlowe, F.J.; Nester, E.O.; Tults. Liquid Crystal Matrix Displays. *Proceedings of the IEEE*. 1971. 59(11):1566-1579.

35. Kmetz, Allan R. Liquid-Crystal Display Prospects in Perspective. *Electron Devices, IEEE Transactions.* 1973. 20(11):954-961.

36. Yongcai Yang and Wenbo Cao Rimin Pan. The Hardware System Design of Smart Color Mark Sensor. *Proceedings of the IEEE International Symposium on Photonics and Optoelectronics*. August 14-16, 2009. Wuhan, China. IEEE. 2009. 1-3.

37. *Color Contrast and Luminescence Sensors White Paper* - EMX Inc. is located at www.emxinc.com/request-whitepaper.html

38. Bajić, Jovan S., Dragan Z. Stupar, Bojan M. Dakić, Lazo M. Manojlović, Miloš P. Slankamenac, and Miloš B. Živanov. Implementation and Characterization of a Fibre-Optic Colour Sensor. *Physica Scripta*, 2014. T162 : 014033.

39. Chen, Hai-xu, Xu-dong Wang, Xin-hong Song, Ting-yao Zhou, Ya-qi Jiang, and Xi Chen. Colorimetric Optical pH Sensor Production Using a Dual-Color System. *Sensors and Actuators B: Chemical*, 2010. 146(1) : 278-282.

40. Wang, Rui, Amlendu Prabhakar, Rodrigo A. Iglesias, Xiaojun Xian, Xiaonan Shan, Francis Tsow, Erica S. Forzani, and Nongjian Tao. A Microfluidic-Colorimetric Sensor for Continuous Monitoring of Reactive Environmental Chemicals. *Sensors Journal, IEEE*, 2012, 12(5): 1529-1535.

41. Park, Seon-Hwa, Dongwoo Seo, Young-You Kim, and Ki-Won Lee. Organic Vapor Detection Using a Color-Difference Image Technique for Distributed Bragg Reflector Structured Porous Silicon. *Sensors and Actuators B: Chemical*, 2010. 147(2) : 775-779.

42. Pang, Shuo, Xiquan Cui, John DeModena, Ying Min Wang, Paul Sternberg, and Changhuei Yang. Implementation of a Color-capable Optofluidic Microscope on a RGB CMOS Color Sensor Chip Substrate. *Lab on a Chip,* 2010. 10(4) : 411-414.

43. Seelye, Mark, G. Sen Gupta, Donald Bailey, and John Seelye. Low Cost Colour Sensors for Monitoring Plant Growth in a Laboratory. *Instrumentation and Measurement Technology Conference (I2MTC) IEEE,* 2011. 1-6.

44. Kwon, Young-shin, and Won-jong Kim. Development of a New High-Resolution Angle-Sensing Mechanism Using an RGB Sensor. *Mechatronics, IEEE/ASME Transactions*, 2014. 19(5) : 1707-1715.

45. Zolotov, Serguei. *System and method for decoding barcodes captured with a color image sensor*. United States Patent 8,079,525, issued December 20, 2011.

46. Zolotov, Serguei. *System and Method for Providing Sufficient Illumination Quality for Barcodes Captured with a Color Image Sensor*. United States Patent 8,500,023. 2013.

47. Zolotov, Serguei. *System and Method for Decoding Barcodes Not Easily Perceptible by Human Vision*. United State Patent 8,584,953. 2013.

48. Paul Franklyn Key, Anthony Ross Lazzara. *Color Mark Detector with Pulsed Source and Synchronous Demodulation*. United States Patent 4,047,023. 1977.

49. Bajic, J. S., Dakic, B., Stupar, D. Z., Slankamenac, M. P., & Zivanov, M. B. The Frequency-Modulated Reflective Color Sensor. *MIPRO, 2012 Proceedings of the 35th International Convention*. May 2012. IEEE. 162-166.

50. O. G. Saracoglu and H. Altural. Color Regeneration from Reflective Color Sensor Using an Artificial Intelligent Technique. *Sensors,* 2010. 10 (9) : 8363-8374.

51. P. K. Yang, J. C. Chen, and Y. H. Chuang. Improvement on Reflective Color Measurement using a Tri-color LED by Multi-point Calibration. *Optics Communications*. 2007. 272 : 320-324.

52. Samuel R. Stein. *Frequency and Time – Their Measurement and Characteristic*. Technical Note 1337. United States : National Institute of Standard and Technology. 2009.

53. IEEE. *Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology - Random Instabilities*. IEEE Standard 1139-1999. 1999.

54. International Organization for Standardization (ISO). *Conformity Assessment — General Requirements For Proficiency Testing*. Geneva, ISO/IEC 17043. 2010.

55. International Organization for Standardization (ISO). *Statistical Methods for Use in Proficiency Testing by Interlaboratory Comparison*. Geneva, ISO 13528. 2005.

56. A. Sahar, M.F.Othman, M.Nasir, E.F.Dierikx, R.P. van Bemmelen, R.P. van Otterloo. Performance Evaluation of NMSL's Developed Calibration System for Timing Devices with Seven-Segmen LCD. *Proceedings of the IEEE International Frequency Control Symposium*. May 19-22, 2014. Taipei, Taiwan. IEEE. 2014. 9-11.

57. SIRIM and University Technology Malaysia. *A System for Measuring Accuracy of Time-Keeping Devices*. Malaysia Patent Application Serial Number PI 2012700484. 2012.