Low Cost LED Based Spectrophotometer

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Abstract

Color printing, whether digital or offset, involves significant prepress work so that the printed output matches what the creative designer specifies. Specialists use spectrophotometers costing thousands of dollars to measure and duplicate the exact colors. In this paper, we describe a multiple LED based ultra-fast, low cost spectrophotometer developed to measure color accurately and repeatedly on a stationary or moving substrate that is tailored for use in a printer for color controls and color management functions. This device also can be used for other fields that demand a variety of color matching including fabrics, paint, wallpaper, plastics etc. We describe the sensing system with device components, architecture and algorithms that make the measurements fast and accurate.

Introduction

The low cost LED spectrophotometer (LCLEDS) device was developed within Xerox and is suitable for deployment in the output paper path of color printers. The goals for the system are: (1) read time < 10 milliseconds, (2) non-contact measurement capability, (3) displacement insensitive over a 6 mm span, (4) color measurement error ≤ 1.0 deltaE (CIELab space).

The approach taken in order to meet those objectives was to employ an array of visible LED die which are sequentially energized to illuminate fused test patches printed on paper moving past the spectrophotometer. A 1:1 image of the patches is projected onto an array of overfilled PIN photodiodes, and the sizes of the image and diode are chosen so that the resulting photodetector current is independent of the displacement between the sensor and the patch to first order [1]. This electrical signal is a relative measure of the reflectivity of the patch at each LED wavelength, and by applying an appropriate spectral reconstruction algorithm, the spectral reflectivity of the patch are determined and the color coordinates are calculated.

System Overview

The LCLEDS head consists of a printed wiring board (PWB) with 8 visible LED's ranging from 430 to 660 nm (see Figure 1 for spectral emission curves), an array of 6 photodetectors [2], a switched integrating amplifier IC, a temperature sensing IC, and a lens assembly. Mounted to the PWB is a detachable bracket, which contains a triggering sensor. The sensor head's embedded controller and its supportive circuitry are mounted on a separate PWB connected to the sensor head by two connectors. It is comprised of the pulsed LED drive and data acquisition electronics, microcontroller I/O interface, microcontroller module, and communication interface. The drive and data acquisition electronics capture voltages from the sensor head that are representative of the spectral reflectivity of the target. The microcontroller I/O connects the sensor drive and data acquisition electronics to the microcontroller module, which contains data and non-volatile program memory, communication circuitry, and embedded firmware. The communication interface transports control, configuration, and data information between the system and the outside world. On command of the embedded controller and with the aid of the spectral reconstruction algorithm, the LCLEDS sensor head output voltages are read and converted to normalized voltages, spectral data, and L* a* b* values.

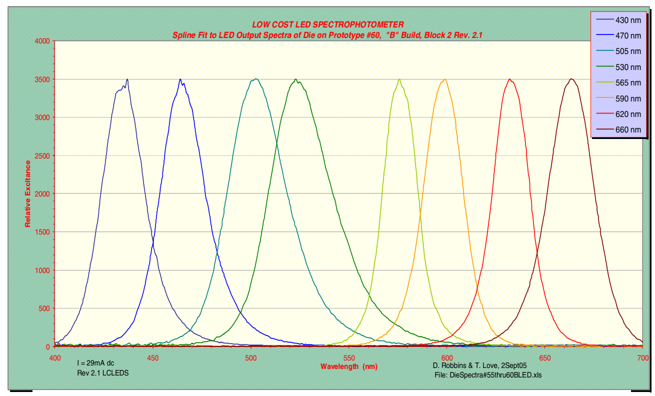

Figure 1: *Emission curves of eight Light Emitting Diodes*

Hardware Description

Figure 2 shows a top outline view and a side section view of the LCLEDS sensor head [2]. The device was designed to be mounted such that the distance from the front surface of the PWBA is 31.5 mm from the test target. The test target can pass by the sensor head in any direction without loss of accuracy. A photograph of one of the prototypes showing the condenser lens, six projection lenses, the PWB, and mounting features are displayed in Figure 3.

The assembly consists of the spectrophotometer and an associated reflective optical switch mounted to the spectrophotometer PWB, which is used to detect the presence of marks registered alongside the colored test patches [3]. The spectrophotometer is shown mounted to one of the media path baffles by means of mounting posts fastened at one end to the PWBA and the other end to the baffle.

The designed operating range of the Low Cost LED Spectrophotometer is +/- 3 mm from the nominal displacement of 31.5 mm. Maximum measurement accuracy and repeatability will occur when the paper traveling past the LCLEDS device is oriented perpendicular to the optical axis of the sensor head. Therefore, the ideal mounting location for the sensor head is a flat region of the paper path. This will minimize lead and trail edge curls in paper and dynamic paper motions and thereby minimize measurement errors associated with these effects.

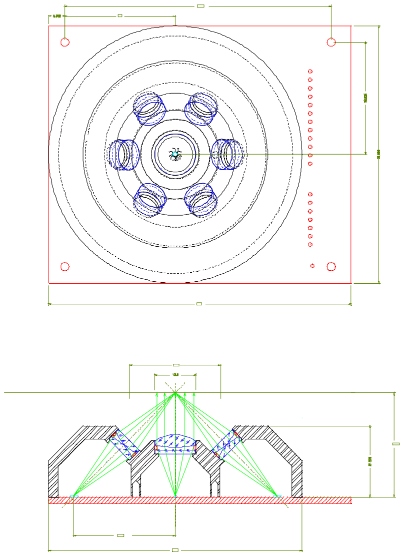

Figure 2: *Outline Drawing of the Low Cost LED Spectrophotometer Sensor Head (Top View & Section View)*

In Machine Location

To minimize the effects of environmental factors such as heat, electrical noise and ambient light, careful consideration is given to the placement of sensing system components within the printer.

A temperature sensor is mounted to the rear of the LCLEDS sensor head PWB to allow temperature corrections to be made during each spectral reading and thus compensate for thermal effects in a machine environment. The principle source of thermal fluctuation originates from heat radiated and conducted from both the fuser and the heated media exiting the fuser and passing through the paper path. Placing the LCLEDS maximally distant from the fuser will yield minimum temperature fluctuation and thus produce minimum error from this source. Locating the spectrophotometer away from the fuser area will also allow the paper to cool and some fuser oil to evaporate before measurements are taken. This will produce results more representative of final document colors.

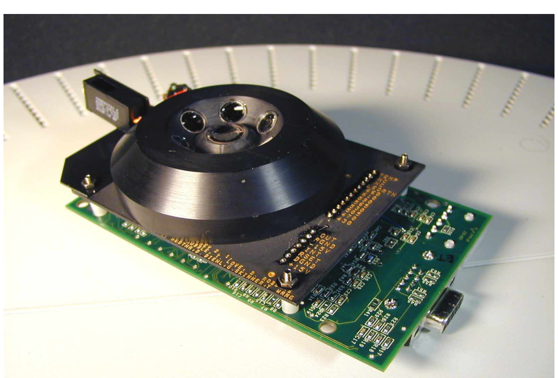

Figure 3: *Photograph of LCLEDS Sensor Head from the Top Showing Details of the Lenses, Housing* and Control Electronics

Since the LCLEDS device is an optical sensor, it is sensitive to illumination from other light sources, as well as its own. These include room lights, sunlight, in-machine lamps, adjacent optoelectronic sensors, and charging devices such as corotrons. Therefore, the LCLEDS sensor head is normally mounted in a dark area of the machine or in an area where a black enclosure or optical stops can be placed around the sensor to prevent external irradiance. The LCLEDS sensor head is also placed in an area where it is shielded from RFI and EMI or located in an area where these are minimized.

Function Overview

The LCLEDS embedded controller consists of sensor drive and data acquisition electronics, two independent microcontroller / DSP systems with associated peripherals, a 12-bit A/D converter, and an RS422 communication interface. It contains resident firmware that provides the spectrophotometer's LED drive and data acquisition sequencing, moving test target synchronization, white tile calibration, color processing and communication functionality.

Spectral Reflectance Measurement

A spectral reflectance measurement consists of a sequence of events as follows. The sensor control microcontroller/DSP sends a digital pulse to the reset input of the Photodetector Current Integrator to drain the integrator of any stored charge. The first of eight LED's is then energized for a predetermined amount of time, at a predetermined current level. The light from this LED is reflected from a color target onto an array of photodetectors, whose output is integrated over the LED's actuation time. During this integration period, the integrating amplifier's output voltage is measured twice by the 12-bit A/D converter. The first measurement occurs shortly after the LED is actuated, the second measurement occurs shortly before the LED is turned off. The first measurement is subtracted from the second and the result is transmitted to a second digital signal processor for color processing. The integrator is then reset and the next LED is actuated. This process is repeated until all LEDs have been actuated and the corresponding response voltages have been collected. The result is a series of eight digitized voltage levels that correspond to the reflectance of the target patch at eight different mean wavelengths. The reflectance spectra of the target patch can be determined from these values.

Sensor Head Temperature

One of the dominant error sources in optical sensors using solid state lamps is variation in lamp radiance with temperature, and a second smaller error source is detector responsivity variation with temperature. Errors from both of these sources are measured together by placing the sensor assembly in an environmental chamber and recording the outputs of the different channels as a function of temperature. A near linear relationship between output and temperature has been observed over the range of temperatures expected in Xerox's reprographic machines and therefore a first order temperature coefficient, $T_{Coeff}(\lambda)$, has been sufficient to correct the raw reflectivities. Following equation, shown for each LEDs, is used to correct for responsivity variation for temperature.

$$V_{TC}(\lambda) = V_R(\lambda) * (1 + T_{Coeff}(\lambda) * (T_S - T_C)) \quad ...(1)$$

where $V_R(\lambda)$ = Raw Reflectivity of the white reference surface at λ taken at temperature T_C, $V_{TC}(\lambda)$ = Raw reflectivity at λ corrected for temperature, $T_{Coeff}(\lambda)$ =Temperature coefficient of the λth channel expressed as a fractional change in raw reflectivity per degree C. A temperature measurement, T_S, is taken at the end of each spectral reflectance measurement by means of the spectrophotometer's built-in temperature sensor. This temperature information is used by the embedded control system's onboard temperature compensation function and is transmitted to the host system. T_C, is the temperature of the sensor, recorded by the temperature sensor immediately after white reference tile calibration which is described below.

Target Measurement

Targets are measured on the paper of interest using a suitable test pattern [3,5]. Each pattern may contain one untoned patch so that the reflectivity of each sheet of paper is measured and the readings of the toned patches adjusted accordingly. These readings are designated $V_S(\lambda)$, where λ is the peak spectral emission of each of the LED's. Immediately after the test pattern is measured, the temperature of the sensor, T_S, is recorded from the temperature sensor so that the target measurements are adjusted for thermal effects using equation 1.

White Balance Calibration

Raw reflectivity is defined as the ratio of the sensor readings of the unknown target to those of the reference tile times the reflectivity of the tile at the wavelength of interest. It is calculated as follows. The equation is shown for single LED.

$$V_{color}(\lambda) = \frac{V_S(\lambda) - V_0(\lambda)}{V_{TC}(\lambda) - V_0(\lambda)} * R_{Ref}(\lambda) \quad ...(2)$$

where $V_{color}(\lambda)$ = Raw Reflectivity of the unknown target color at λ, $R_{Ref}(\lambda)$ = Reflectivity of the calibration tile at λ. $V_0(\lambda)$ = Raw output of the detector when the LEDs are not illuminated. In order to maintain optimum reflectance voltage resolution, the spectrophotometer sensing system is periodically calibrated to a standard reflectance surface.

Target Synchronization

In order to perform spectral measurements as the target document passes the spectrophotometer head, real time target synchronization is required. The synchronization apparatus consists of trigger marks on the target document, a trigger mark sensor working in conjunction with electrical interface circuitry and a firmware synchronization process, both of which are implemented on the embedded controller [5]. In addition to determining precise timing for individual color patch measurements, it is necessary to insure that the present page is a target document of interest. To accomplish this, the host color correction system is responsible for issuing a "Read Patches" command. This command results in the Spectrophotometer Controller entering its "armed" state. The paper path is cleared before the "Read Patches" command is issued.

Spectral Reconstruction

Spectral reconstruction is the process of converting the raw reflectivities of the unknown target color (output of equation 2), to a function representing the reflectivity across the visible spectrum and takes care of effects introduced by the spectral emission width of the LED's. In this section, the approach used to convert integrated sensor measurements to fully populated reflectance spectra with reflectance values at specific wavelengths is described.

Algorithms in the sensor utilize a reference database that contains training samples, which indicate reflectance spectra and their corresponding LED sensor output. A modified version of the Dynamic, Least Squares-based (DLS) spectral reconstruction algorithm is used to reconstruct spectra [6]. The DLS algorithm is "dynamic" because it gives greater importance to the data from the training samples in the neighborhood of the color sample under measurement. This is done using linear operators. Whereas, the modified version implemented in the sensor uses a cluster of training data to construct the reconstruction matrices. In simple terms, if we have a spectral reconstruction matrix determined through an offline characterization process, the spectral reconstruction using DLS algorithm would require solving the following equation:

$$S = AV \quad ...(3)$$

Where A is the spectral reconstruction matrix, V is the vector containing sensor reflectivities from equation 2 for the sample color under measurement; S is the spectra for the sensor reflectivities. For a clustered training data, spectral reconstruction matrix, A is unique to each cluster [7]. Also, if we use the linear offine model during the offline process while determining the spectral reconstruction matrices, and we are required to reconstruct spectra between 400 to 700 nanometers at 10 nanometer wavelength intervals, then the matrix A is of size 31 x 9. The reflectivity vector, V is of size 9 x 1 and the spectral function, S, is of size 31 x 1.

During the offline training process, which is also called sensor characterization process, the reference database is generated by measuring the reflectance spectra of some set of reference training colors, with an accurate reference spectrophotomer, such as an XRite 938 spectrophotometer, and their corresponding LED sensor outputs, with the sensor vector V. Clearly, the information included in the reference database, is a mapping from reflectance spectra (as measured by a reference spectrophotometer) to sensor outputs (as measured by the sensor V) formed by a set of N spectra to voltage measurements, denoted as:

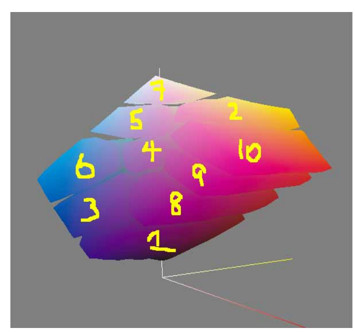

***Figure 4**: Clustered Sensor Characterization Gamut*

$$[S_1\ S_2\ \ldots S_N] \in R^{n \times N} \longrightarrow [V_1\ V_2\ \ldots V_N] \in R^{l \times N}$$

where $S_1\ S_2\ \ldots S_N$ are the vector elements containing the N spectral curves, each curve containing 31 elements, i.e., reflectance values ($n = 31$), and $V_1\ V_2\ \ldots V_N$ are the vector elements from the LED sensor outputs. Here, each curve contains 31 elements because an XRite 938 spectrophotometer, which outputs 31 values, is used as reference sensor. $V_1\ V_2\ \ldots V_N$ are each a vector including 8 normalized voltages corresponding to the 8 LED color sensor outputs. N is a predetermined number based on certain color gamut specifications for the color sensor. Generally, the larger the gamut, the larger N will be. As an example, N is used as 3131 colors spread around the color gamut.

The reference database (or training colors) is partitioned into a plurality of clusters, and an appropriate centroid is determined for each cluster using vector quantization [K-means (also called LBG)] algorithm [7]. An example of the clustered sensor characterization gamut for 10 clusters is shown in Figure 4 above.

During target color measurement, immediately after solving equation 2, the vector, *V*, which is the measurement vector of the sample under consideration, is formed. Each cluster is assigned by comparing the Euclidean distance between the centroids and the vector, *V*, and picking the cluster index which corresponds to the minimum Euclidean distance. This cluster index is then used to assign the spectral reconstruction matrix and solve equation 3 to obtain spectra.

Sensor Performance

Performance table is shown below in Figure 5 for 10 different sensors when measured at speeds 1024mm/second (approximately 200 pages per minute), measuring and transferring as much as 11 spectral curves per page each with 31 reflectance values between 400nm to 700nm for 182 IT8 sample colors spread over the printable iGen3 gamut.

Performance Metric	Peak to peak repeatability with 10 measurements per patch			Accuracy wrt X-Rite 938		
Sensor numbers	IT8 Patches			IT8 Patches		
	95%	Max	Mean	95%	Max	Mean
1	0.52	1.36	0.23	1.24	1.66	0.70
2	0.61	1.41	0.27	1.23	1.66	0.66
3	0.53	1.35	0.23	1.20	1.65	0.66
4	0.60	1.38	0.26	1.20	1.52	0.61
5	0.55	1.35	0.24	1.25	1.49	0.64
6	0.49	1.42	0.22	1.32	1.67	0.74
7	0.74	1.50	0.32	1.28	1.54	0.66
8	0.52	1.33	0.24	1.32	1.61	0.64
9	0.64	1.23	0.29	1.30	1.65	0.65
10	0.61	1.25	0.27	1.18	1.67	0.61
Average	0.58	1.36	0.26	1.25	1.61	0.66

Figure 5: *Sensor Performance data (Peak to peak repeatability and accuracy) for 10 different LCLED spectrophotometers*

Summary

A low cost high speed spectrophotometer device is developed that allow realtime control capabilities in the press to adjust the toner/ink and or process. This device can measure spectra of color patches on a moving paper moving past the spectrophotometer at high speeds and at variable speeds. LEDs are switched between 90us – 500us, with a total read time of <10ms per color patch. It has non-contact measurement capability, displacement insenstive optics to the moving paper over a total vertical displacement of 6mm span which is produced with specially shaped onboard glass lenses. Color measurements are repeatable to <0.26 average deltaE peak to peak in CIELAB space (for 182 IT8 evaluation colors sampled over the printable gamut of iGen3 printer with each color measured 10 times insitu) due to novel signal conditioning methods offered by correlated double sampling techniques. Accurate spectral reconstruction is achieved to benchmark levels, <0.66 average deltaE CIELAB, for all printable colors to a known sensor using color space clustering, cluster assignments and reconstruction algorithms, all done automatically inside the embedded processor during each spectral measurements. The above combination of components and algorithms enables performance levels that are comparable to spectral measurement systems that typically cost hundreds or thousands of dollars more than the expected production cost of this new design, and packaging flexibility that allows this design to be used for many other embedded applications [8].

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