Challenges of Embedding a Spectrophotometer inside a Printer

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Abstract

Professionals of the graphics arts industry require color reproduction accuracy and consistency across a large and open set of media. For color critical applications this typically means the use of a color measurement instrument. All of these tasks can be carried out today with off-line measurement devices and the corresponding software, but such systems are not easy to use, not integrated into the workflow, and expensive. Embedding color measurement capabilities inside a printer tries to solve most of these issues. This paper explains the specifications of the embedded spectrophotometer of the HP Z-series DesingJet Large Format Printers, the challenges that were found during its development and the improvement of the colorimetric performance of the printers that are using it.

Introduction

Predictable results are essential to professional color workflows (professional photography, digital fine arts, graphic design, pre-press, print service providers). Prints must match the user's expectations for accurate colors on the loaded media; grays should be neutral over the full dynamic range from white to black, and the results must be consistent print-to-print and printer-to-printer. Both color consistency and color accuracy are essential.

Color Consistency

Color consistency ensures that the same input produces the same output, print after print and printer to printer. Consistency comes from controlling many factors in printer design, manufacture, and operation. Digital inkjet is currently one of the most used printing technologies. Manufacturing tolerances of several printing workflow components and the influence of the environmental conditions affect to the lack of color consistency of some of these systems [1]: volume of the fired ink drops, dyes or pigments concentration, white point of the media, ink to paper interactions, etc.

Color Calibration

Calibration refers to the process of adjusting a device to a known state. Then inkjet printers' calibration is necessary. A possible strategy is to adjust the different components during the manufacturing process, but this doesn't correct the tolerances of replaceable parts (print-heads, ink containers, media, etc.) or the effect of the environmental conditions. Taking everything into consideration requires precise and repeatable measurements of printed color samples both within and across printers.

The color calibration is obtained in most systems by printing and measuring a chart of gradients of the primary inks colors, and calculating then a new calibration LUT that will be always used before the halftoning phase. Under some circumstances this process is also called "linearization". In most implementations, for N primary inks, the calibration LUT consists of N one-dimensional transfer functions that both equalize the maximum optical density of each ink to a specific value and compensate the dot gain effect to obtain perceptually uniform color gradients (1D algorithms approach). This type of density compensations and linearizations has proven to be sufficient in most cases to correct for drifts in lightness and chroma [5]. There are other calibration methods that take into consideration crossed effects between planes (2D, 3D). They require multidimensional LUT and are able to correct for hue changes [2][3][4].

Color Accuracy and Verification

Color consistency is necessary but not sufficient to produce professional image quality. Consider the example of a print run of 100 copies of a retail poster: if the colors are the same across the batch, but they do not match the client's intended color, then the color for the batch of prints could be described as consistent but not accurate. Color accuracy ensures that colors are printed correctly.

Color accuracy is assured by a color map or ICC profile that translates desired color specifications into printable color values. This requires a characterization chart to be printed, measured with a color measurement instrument, and a color map or ICC profile to be built. Normally this process is done once in the factory for each different paper type and / or device configuration. Although this provides a good approximation, there is always some remaining color variability that cannot be eliminated this way, e.g. due to changing environmental conditions or to the use of unknown paper types. Hence for best possible accuracy, custom color maps or profiles need to be built in situ, which requires the use of a color measurement instrument.

Color verification means to certify that the printed color is indeed the color that was requested. For color critical applications this typically means instrumental verification, using a color measurement device. The following figure shows an example about where the color calibration and ICC profile data are used in a 12 inks printing workflow.

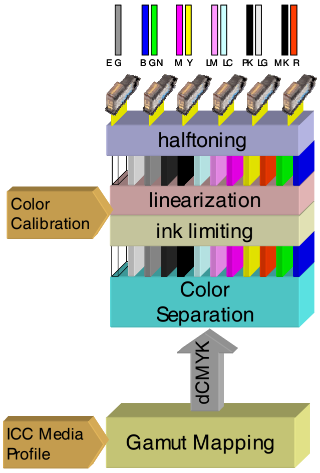

Figure 1. *Color calibration and ICC profile*

Problem Description

All of the above processes can be carried out today with off-line measurement instruments and the corresponding software. These solutions are complex, not integrated into the user workflow, and expensive. Users demand embedded solutions fully integrated in their workflows.

Then, the objective is to provide an embedded, automatic, easy to use, and fully integrated solution that meets or exceeds the performance of existing off-line solutions. Besides basic challenges such as reducing the size of the measurement device or integrating it with the SW for each printer unit, other new challenges appear compared to off-line solutions.

External Illumination

All the spectrophotometers in the market use their own known source of illumination. Any influence of external light while measuring the sample may modify the colorimetric performance of the device. Off-line solutions can have fixed environmental conditions. However, printers have covers and holes where indirect light may go through. Then, printer designs must assure that no straight light can go through any part of the system and hit the media while taking color measurements.

Spectrophotometer Calibration and Protection

All the color sensors need to be calibrated by the manufacturer during production to ensure the accuracy and consistency performances. Besides this end of line calibration, they also need continuous recalibration while being used to avoid high level of inaccuracies in the measurements due to changes in the emitting light and in the capturing sensor performances. The type of calibration depends on the sensor technology. The main way of recalibration is based on measuring a known reference target (a ceramic white tile, for instance) and readjusting the internal light emitter and the capturing sensor to the measures of the reference target.

Then, the whole color performance of the measuring device is based on assuming that the reference behaves always in the same way and that it doesn't change with time. For external color measurement devices this assumption is most of the times valid, because the environmental conditions are under control. However, the environment inside a printer is full of aerosol (little particles of ink on the air), the sensors move with the carriage of pens at high speeds, and the humidity and temperature may change a lot. Then, embedded color measurement solutions must protect the reference as much as possible. Figure 2 shows an example of aerosol contamination of a calibration tile when it is not properly protected.

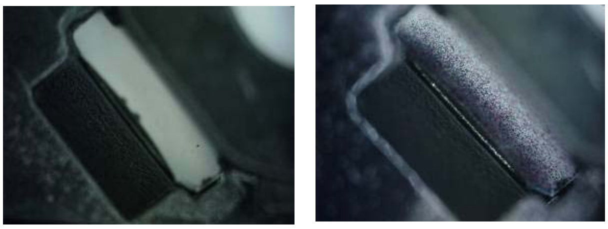

Figure 2. *Example of calibration tile contamination with aerosol particles*

Paper Thickness and Position Tolerances

Off-line spectrophotometers have measurement variability depending on the distance between the device and the media. That is why most of them touch the sample while taking measurements or are recommended to be used at a constant focal distance. The contact measurement assumes that the sample is dry enough and that it is not going to be damage.

Non-contact instruments are more efficient (higher measurement speed) and prevent damaging or marking printed materials while they are being measured. Inkjet prints require some time until the ink is totally dry and the colors are stable. Then, embedded solutions are very likely to use non-contact devices.

Printers accept a wide variety of media with different thicknesses, which varies the distance between the paper and the embedded spectrophotometer (assuming it has a fixed position). The positioning of a device inside a printer has also a mechanical tolerance. Then special optical components must be designed to take into account the height variation within specified tolerances. The illumination system has to take also into consideration this working distance variability to assure enough illumination uniformity in the measurement area across the whole distance range. In these solutions is then fundamental to control the distance between the device and the sample to measure.

If the embedded spectrophotometer could vary its position to touch the sample or to assure that it is always located at the same distance from the measurement sample, the implementation would be more robust offering higher color accuracy and consistency across a wider range of media. However, this solution would have higher cost, higher overall measurement time and the sample could be damage if it isn't dry enough.

Measurement Patch Size

Another side effect of the variability between the spectrophotometer and the sample to measure is that the measurement patch size requires being larger than the aperture size would suggest, since the instrument has a wider field of view than a contact instrument with the same measurement aperture. Depending on the measurement distance, the optimum measurement spot size also changes. Various printer mechanical factors can contribute to measurement positioning inaccuracies, so to assure the quality of the measurements embedded solutions may require bigger measurement patches than equivalent off-line devices.

Proposed Solution

The HP Designjet Z series printers include an embedded spectrophotometer (from now on referred as ESP) instrument which is used for printer calibration and profiling. The ESP with i1 Color Technology from X-Rite™ is a precision instrument that is mounted on the printer carriage. Its completely self-contained optical system and electronics produce CIE Lab, CIE XYZ, spectral, and Density Status E outputs.

Although the ESP design allows the influence of up to 300 lux of external light to make measurements with color variability below 0.4dE76, the printers have been designed to limit as much as possible the ambient light exposure, reducing then this variability to minimum levels. A white calibration tile is embedded in the ESP and it is protected by a mechanical actuated shutter. This shutter has been designed to avoid contamination (dust, aerosol, or any other particle) of the tile while it is in its closed position. This protection disappears while the ESP is taking measurements (the shutter is open). Then, to avoid aerosol contamination, measurements cannot be taken while the charts are being printed.

The design allows taking color measurements to perform color calibrations and make ICC profiles for the wide range of media thickness supported in Z-series printers (2 mm). The minimum measurement spot size is around 10 x10 mm. Bigger patch sizes are used to include mechanical tolerances and avoid flare influence from adjacent color patches when. Smaller sizes are not recommended to assure the desired levels of color accuracy and consistency.

All these considerations ensure reliable, media independent measurements that are traceable to international standards. Table 1 summarizes the main characteristics of the ESP and figure 3 shows where it is located inside the printers.

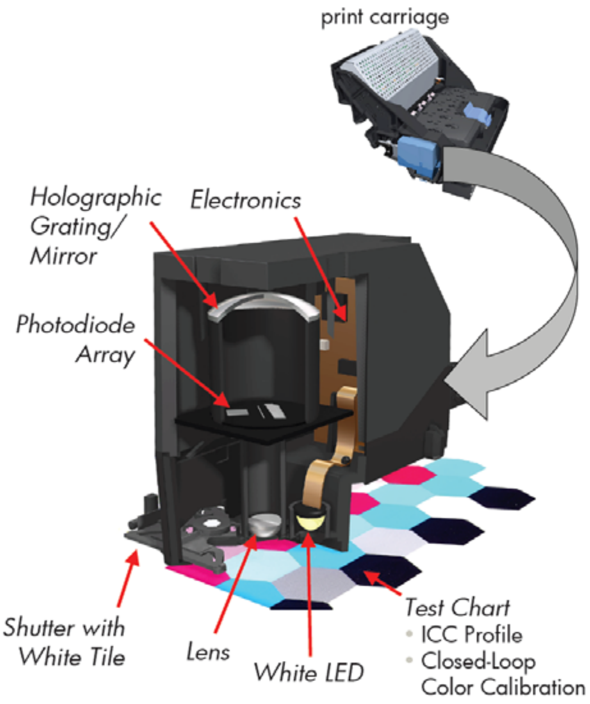

Figure 3. *The ESP as mounted on the printer carriage*

Colorimetric Performance Results

Professional photographers and pre-press users have been using inkjet printers without ESP for long time. There are also printers in the market that just incorporate and embedded densitometer. The question that arises is: How much does an ESP improve the printer color accuracy and consistency?

Printers without any embedded color sensor cannot automatically create an ICC profile or make a color calibration without user intervention. To improve the color accuracy of these systems, external spectrophotometers and SW solutions need to be used to create custom ICC profiles or color calibration tables. Under these circumstances color accuracy comparisons between printers with and without ESP do not make sense, because similar levels of color accuracy performances are obtained if external spectrophotometers are used. However, once a specific color accuracy performance is obtained, print after print and printer to printer color consistency can be compared.

A test was conducted to compare the color consistency of three inkjet printing systems. The first one (NONE) didn't have any embedded color measuring device. Another (DENS) had an embedded pseudo-densitometer without an internal calibration target (the white point of the loaded media was used to calibrate it) and without a shutter protection. This system could create internal one-dimensional calibration tables measuring printed color ink densities. The third one (ZESP) was similar to DENS but using the proposed ESP solution.

The test lasted for several weeks. During that time the printers had their print-heads and ink cartridges replaced. A change of print-heads or ink cartridges was considered as a new printing system. Finally, 6 NONE, 68 DENS and 37 ZESP systems were used and around 300 prints were done with each one of them. The test sequence was always the same:

- Assure the printing system has good image quality
- Perform an internal color calibration (Not applicable for NONE systems)
- Print a chart of 88 uniformly distributed colors

For each of the three system types all the printed charts were measured with the same external spectrophotometer. The color consistency was analyzed and results are expressed as the Mean Color Difference form the Mean (MCDM) in table 2. The table shows the 50 and 95 percentiles and the maximum color difference (in dE76) between all the printed charts and the average color of each system. This measurement may be considered as an indication of the printer to printer color consistency.

Table 1. ESP with i1 Color Technology compared to the X-Rite™ i1®

	HP ESP with i1 Color Technology	X-Rite ™ i1®
Spectral Range	400 – 700 nm	380 – 730 nm
Spectral Bandwidth	20nm	10nm
Colorimetry	CIELAB, CIE XYZ, spectral, Density Status E	CIELAB, CIE XYZ, spectral, Density Status E, T
Illumination	White LED (UV-cut)	Gas-filled tungsten (A)
Calibration	Integrated white reference	External white reference
Spectral analyzer	Holographic grating, diode array	Holographic grating, diode array
Sensor Accuracy	avg. < 1.1dE94, max < 2.1dE94	N/A
Single Sensor Repeatability	avg. < 0.1dE94 on white reference	avg. < 0.1dE94 on white reference
Sensor-to-Sensor Repeatability	avg. < 0.4dE94 on BCRA tiles	avg. < 0.4dE94 on BCRA tiles

Conclusions

ESP is a high quality embedded spectrophotometer that compares favorably to well-known instruments such as the X-Rite/GretagMacbeth EyeOne and Spectrolino devices. It is specified, designed and qualified to provide trouble free operation for the life of the Z series DesignJet printers.

Table 2. MCDM of three inkjet printing systems

dE76	50 percentile	95 percentile	Max
NONE	1.3	5.1	7
DENS	1.1	3.2	7.8
ZESP	0.5	1.5	3.2

Systems with ESP have proven to have twice better printer to printer color consistency than systems with embedded pseudo-densitometers. The ESP and the pseudo-densitometer are devices with different characteristics, but the color calibration algorithms used have been the same and they are based on just measuring the optical density of the printed color patches. Then, the main influence to the different consistency performances was the measurement repeatability of the measurement device itself. A higher improvement could have been obtained if multidimensional LUTs had been created during the calibration process. Other obvious advantages for having a protective shutter as the lack of contamination on the illumination components, the capturing lenses, or calibration tiles along the life of the printers were not included in the experiment. Printers with embedded color sensing devices without proper protection will show higher color measuring drifts along its life.

The level of improvement is even higher when comparing performances with some systems (NONE) that do not have any embedded color sensing capability (around three times better color consistency performance). These differences are reduced if the same external spectrophotometer and color calibration algorithm are used for all the printing systems. However, this adds complexity and cost to the overall printing solution.

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Author Biography

Óscar Martínez is a color engineer in the “Imaging and Color – Measure” group at the large format printer division of Hewlett-Packard in Spain. He has a BS in Telecommunications Engineering (1995) and a MS in Electronics Engineering(1997) from Ramon Llull University, a MS in Computer Vision(2004) from UAB University, and is finishing his PhD in Optics Engineering in the UPC University. He has worked for the last 12 years on the development of large format printers, copiers and scanners. His current research topics include image quality (specification and measurement), image processing, color pipeline and workflows, user interaction with printers’ color technologies, and color sensors development.

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