Systems for Image Quality Control in Inkjet Printers

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Abstract

Inkjet is a conceptually simple digital printing technology. However, printing defects can be observed due to both small inaccuracies in the system and aging effects. Some of those defects have very identifiable sources, thus enabling correction techniques to restore image quality. In its simplest way, the correction involves visual inspection of specifically designed patterns and closing the loop through the driver or through actuation on printer knobs. Generalization of this approach has lead to automated, increasingly sophisticated measurement and correction techniques. Nowadays inkjet printers are able to measure nozzle health with optical systems and to use redundancy and other techniques to hide the defects. Media advance and printhead position can be automatically calibrated also by optical means. Color consistency, including paper induced variability, can be assured by in-printer densitometry measurements and automatic calculation of correction look-up-tables. In addition, advances in inkjet system design and manufacturing have enabled exponential growth of the printing systems' capabilities. Measurement and correction systems have evolved to accommodate that growing demand. The results are significant reductions in user intervention and maintenance costs, while increasing productivity, image quality and consistency. Most of this progress has been made while keeping the cost of the systems at a fraction of the industry standards.

Introduction

In a broad sense some systems for image quality control in inkjet printers appeared shortly after the first inkjet printers. They were the response to image quality defects that were intrinsically related to the technology itself and to the architecture of the printers. We include in this category from relatively simple aids for calibration, either at manufacturing line, by service personnel or by the user, up to fully automated close loop systems operating in real time. The common denominator of all those systems is the direct or indirect measurement of a parameter of the system that has an impact on the print quality and the provision of a mean for correction based on that measurement. Their objectives are to improve consistent image quality consistency, while simplifying the use of the printer.

Inkjet Specific Sources of Image Quality Defects

The most important systems for image quality control are those that correct very visible image quality defects that occur very often.

Paper feed error is probably the most critical, because it occurs after every printing pass, and because moving the paper incorrectly, even with relatively small errors, produces very visible banding. The media advance accuracy required for defect free printing at high resolution requires extremely high precision in the shapes and dimensions of all the involved mechanical parts. Such precision is expensive, and given product cost constrains, the calibration methods that measure repeatable errors and compensate for them are very useful. In addition, inkjet printers in scanning configuration have difficulty to accurately position the paper after advancing it, due to servo errors and slippage of paper relative to drive rollers. Not surprisingly, a significant effort has been dedicated to this problem. Despite significant progress, media control is a field of active research since growth of swath heights increase the visibility of media feed related defects.

Defects related with nozzle health are next. In the past, one single missing nozzle could mean replacing a relatively expensive cartridge. In parallel, growing number of nozzles favored the occurrence of missing nozzles. The reduction of drop size reduced the perceptibility of the defects related to missing nozzles, but it was still difficult to consistently print perfect images given that, statistically, the chances for all of a very large number of nozzles to be in perfect conditions are small. However, for thermal inkjet, the very source of the problem is part of the solution. Improvement in manufacturing techniques has enabled a sustained exponential growth of the number of printable drops per second, see figure 1. The progress has been comparable to the Moore's Law in microelectronics, which predicts doubling the density of transistors in an integrated circuit every 18 months. The system can easily be designed with a large extra capacity for drop ejection, also known as redundancy. Whenever a nozzle is faulty, it is very likely that other nozzles can take on its duty. The results of such technique are dramatic, allowing the printheads to survive in the system several times longer than without the correction, with no visible degradation of print quality, figure 2.

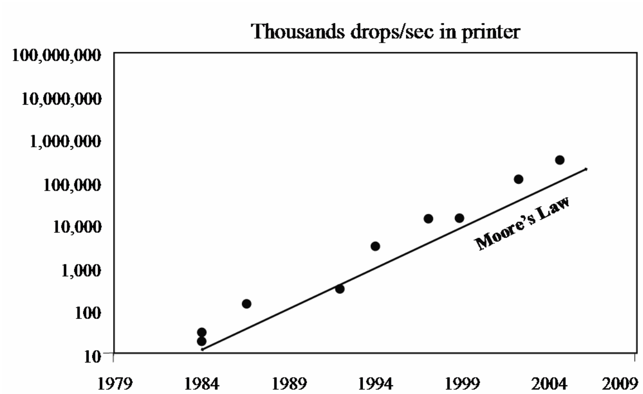

Figure 1. Exponential growth of drop ejection capability

Figure 2. Samples printed with printheads suffering catastrophic damage without correction (left) and after automatic detection and correction (right)

Timely measurement of the health of every nozzle when there are many of them is, however, a rather difficult technical problem, and growth of the number of nozzles and reduction of the drop size requires fast advances and substitution of the technology as will be seen below.

Inaccurate position of dots in paper relative to each other is another typical defect. It may be seen as mis-registration, vertical and horizontal banding, rough edges, stepped vertical or diagonal lines, hue changes. The sources are multiple types of static and dynamic mechanical imprecision in the printheads, their carrier, its path and drive system and the structure of the printer itself. Some of those can be calibrated on the factory line or by service personnel. Others, because the errors change often, require regular measurement and correction, known as alignment. Again, the growing number of nozzles in the system stresses the capabilities of the technology.

Color reproduction is affected in multiple ways. Drop volume variation is the main offender, closely followed by differences in how each individual paper reproduces color, and even by environmental factors, especially humidity.

Finally, a diversity of operational factors can create image quality degradation. Printhead temperature due to high duty cycle is an example. High temperature reduces the viscosity of ink which increases the drop volume and alters the tail breaking process, creating spray. Monitoring or forecasting the printhead temperature and changing the printing process to avoid exceeding certain limits may help optimizing the system.

System Design Considerations

Not all inkjet printers incorporate control systems for all the sources of image quality problems. First of all, printheads are manufactured with different technologies and this greatly impacts what sort of problem is a priority and how much it can be successfully corrected. For example, achieving high degree of redundancy is much easier with thermal inkjet than with piezo inkjet. However, fewer nozzles and longer nozzle life in piezo inkjet printers reduce the need for correction. It is important to note that, to some extend, it is a matter of choice linked to strategic decision about how to create and deliver technology. The value added by a control system will be different depending on printhead technology, product positioning and printer architecture.

The product category is another important factor. Inkjet printers populate the low price segments and are usually under very strong cost pressure. The cost of measurement devices may not be affordable. Often control systems appear in the higher end applications, such as wide format, and are exported to other product categories after significant refinement and cost reduction.

Capability to manage complexity is another very important factor. Successful implementation and integration of measurement devices and correction algorithms is a lot more difficult than it might appear. Significant resources must be devoted to develop and qualify technologies and to implement them in products. Often some control systems are not robust enough, and create usability issues or new image quality problems. The learning curve is rather long and it requires large and very well managed organizations to successfully develop some of the systems. Finally, the ability to leverage the technology into many products is necessary to make the investment worth it.

Dot Placement Error Measurement Systems

Methods for guaranteeing proper dot position on the printed substrate have evolved in the past years. First systems involved printing some test patterns where the user had to choose via printer front panel or driver the most suitable one. That method was used from very-low cost home printers like the DeskJet 500 series from HP up to wide format printers like the NovaJet 3 series from EnCAD. This system had the only cost of the used media, but it relied on the user for providing the feedback to get accurate results.

In the middle of the nineties, systems became more sophisticated. New methods started to do automatic calibrations without user intervention. These systems are primarily based on a light source like one or more LEDs, illuminating an area of the printed substrate and an optical detector receiving light reflected or diffused from the substrate. If this application uses an LED and a single detector, several scans need to be done, wasting time that can reach several minutes. As printheads grow in number of nozzles and resolution, these applications become more demanding in terms of speed and accuracy. The latest technology can be found in OCE TCS400 where the system uses a fluorescent lamp and a linear CCD detector[4] so it benefits from the high resolution the system has and also allow massive parallel detection by aligning the whole printhead height in a single scan.

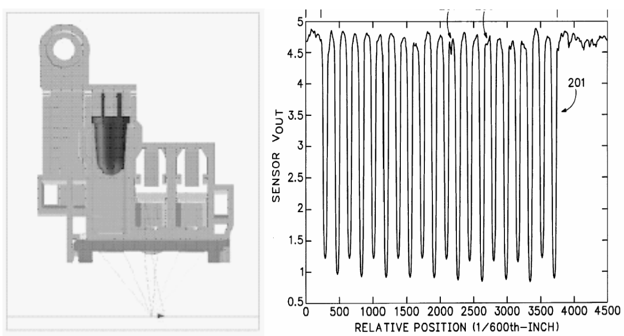

Figure 3. LED-Based system used for several IQ control corrections, and signal read by the same sensor using the relative position method

Although sensing systems can be very different, from human to CCD-Based, they all have in common the use of test patterns. These patterns consist of printing with one or several printheads at different printing speeds and directions in order to measure the offsets from the expected nominal positions. The pattern and algorithms chosen are critical on the final accuracy of the system. A description of main pattern types follows:

(1) **Interference Method**: this method prints one color over another with predefined offsets among them.[5] Then, the image quality control system scans the pattern and gets a curve with different values depending on relative offsets. By locating the minimum of the scanned curve, i.e where the drops of the different pens are best aligned, the proper offset among the printheads can be found.

(2) **Relative Position Method**: a test pattern is generated with some square-like shape[6] or similar and scanned using the optical sensor. Each of the peaks on the signal can be fitted to a specific curve depending on the pattern printed and systems used for acquiring the image. Samples are normally taken at a lower resolution due to bandwidth constraints and then signal is fitted to a sinusoidal, Gaussian or the closest shape. After the fitting to a certain function, we can generate a higher resolution signal that allows detecting more precisely the peak position of each pattern in the scan direction. The best curve fitting is a function based on the convolution of the pattern shape and the sensor impulse response. By proper sensor characterization and pattern election the most accurate results can be achieved, up to 1/2400 inch for a 600 samples/inch scan. Thus, up to 4 times higher accuracy than the original scanned data can be achieved.

After measurement has been done, the methods for compensating these errors are mainly the next:

(1) Mechanical adjustment of printhead position, either automatic like OCE TCS400 and DesignJet600 or manual like EnCAD NovaJet III.

(2) Printhead firing sequence change through electronic methods. By changing the nozzles firing order or the relative firing sequence a really high resolution can be achieved, up to 2400 dpi as the firing timing can shift in the order of tenths on nanoseconds.

A special case from Epson is presented by Toyohiko et al.[7] By using special calibration algorithms during printer and printhead assembly, some values can be stored and used by the printer in order to compensate for the deviations without the need of algorithms when the printer is in operation by the customer.

Color Measurement Systems

Methods for color control aim at improving color accuracy and color consistency of the printed image. By color accuracy we mean the printer capability to print a specific color matching the expected one, while color consistency refers to the printer capability to keep the color printed the same no matter what environmental and operation conditions (printheads, temperature, substrate...). A user will expect its printer to be as good as possible in both aspects.

The simplest system uses one or several LEDs and a detector like the ones shown in the previous section. In this case we perform a simple color density measurement. Depending on how well characterized and stable are the light source and detectors used, higher accuracy and repeatability can be achieved. However, this system only allows densitometry values, so its capabilities are quite limited.

The most accurate system uses real or almost colorimetric data with a device capable of providing such data from the printed pattern. In this case, the device used for measurement is a real colorimeter or spectrophotometer. These measurements are quite slow, in the order of seconds for each patch to allow color measurement error below 0.5 ΔE in CIELab space. In this case we can achieve both color accuracy and color consistency.

A common problem is system warm-up. Thus, algorithms that provide signal stability need to be in place. Very stable white and black points used as absolute references are also necessary.

The patterns normally consist of printing color ramps with different ink densities for each printer primary. Depending on the desired accuracy, more patterns can be printed and secondary color ramps may be used for higher gamut coverage.

The simplest adjustment method consists of getting the transfer function from color density to some colorimetric value like L*. Through curve fitting or other algorithms like look-up tables a linearization transfer function can be calculated and applied during halftoning as shown in figure 5. Note that this method does not ensure accurate color, which must be obtained via printer profiling and color management, nor does it ensure color matching from one configuration to another.

With colorimetric data, more complex algorithms can be done achieving the already said color accuracy.

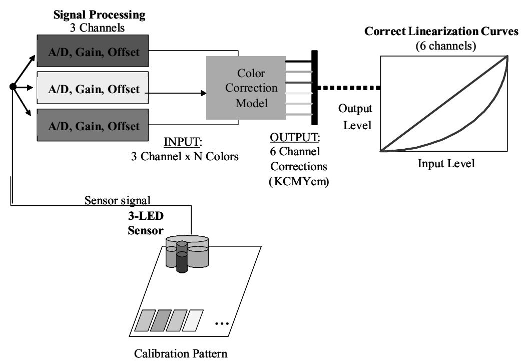

Figure 5. Color correction scheme based on primary linearization for a three-LED system on a 6 color printer

Table 1. Some Systems Used in Inkjet Printers Currently in the Market. DPE Stands for Dot Placement Error

Printer	DPI	Control	Technology
HP DesignJet 130	2400	Color and DPE	LED based
EnCAD NovaJet 1000i	1200	DPE	Human based
OCE TCS400	600	Color, DPE and nozzle health	CCD based
Epson SP4000	2880	Color, DPE and nozzle health	LED based
ColorSpan Displaymaker 72s, X12[8]	1800	Color, DPE and nozzle health	CCD based
Canon W6200	2400	DPE	Human based

Nozzle Health Measurement and Correction Systems

The simplest way of detecting missing nozzles consist of printing a test pattern (figure 6) that is subsequently examined by the customer in order to feedback the system with the information about the failing nozzles. The pattern is designed in such a way that each of its features can be associated to every single nozzle of every individual printhead. This solution can be found in some of the mid-nineties products like the EnCAD NovaJet IV. This approach has some obvious disadvantages: it requires the intervention of the user, making it time consuming and error prone, and it causes some media waste in every test cycle.

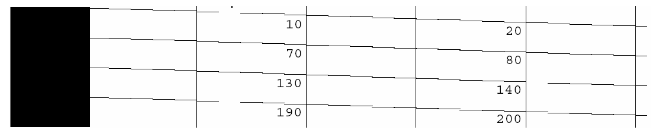

Figure 6. Example of a test pattern showing missing lines caused by failing nozzles

Most of the above mentioned drawbacks can be overcome by adding to the system some way to automatically analyze the printed pattern. Different types of optical sensors, ranging from simple light sensors plus LED illuminators to more complex CCD or CMOS image sensors can be used for this purpose. One example of such implementation can be found in the HP Designjet 2000CP family of wide format printers. The same sensor used to measure the dot placement error (figure 3) is used to scan the pattern in order to detect the missing nozzles.

None of the previous techniques is really suitable for today's typical printer, mainly because of the impact on throughput and productivity caused by the huge number of nozzles to be tested. Alternative systems have been devised, usually requiring neither a printed pattern nor the user intervention. The most common approach consists of using a sensor to detect whether some amount of ink is ejected by a nozzle in response to a firing command. This sensor is commonly referred to as drop detector and may use several detection technologies. An optical drop detector (ODD) uses a light emitter (either IR or visible) plus an associated receiver to create an optical barrier through which the ejected drops travel. The amount of light sensed by the receiver (detector) changes in presence of a drop and its output signal can be further processed to decide not only whether a drop has crossed the barrier but also to ascertain some of their characteristics (drop size and velocity, etc.). Such a type of optical drop detectors can be found in devices like the HP Designjet 1000 series and the Epson Stylus Pro 10000, among others.

A quite different technology is used in the so called electrostatic drop detector (EDD). These devices rely on measurements of the charge induced in a drop of ink traveling through an electrostatic field created by a relatively high voltage bias (30 to 100V). The charge collected into a sensing plate is converted into a useful output signal by means of the appropriate amplifier stage. The EDD potentially allows the system to measure also several printhead-related parameters besides the presence of the drop, such as its mass.

The continuous increase in both the number of nozzles and the number of printheads, together with the need to keep the testing time at reasonable length, has led to new systems implementing a massive parallel detection scheme.[9] They are a radical evolution of the classical ODD in which the typical narrow light beam has been replaced by a collimated light plane, perpendicular to the drop travel direction and covering the full printhead width. The single receiver is also substituted by a multi-channel receiver (a line CCD, for instance). This arrangement enables the detection of simultaneously ejected drops and opens also the possibility of testing additional parameters beyond the pure drop presence. The weight and velocity of the drop, as well as its trajectory can be calculated by means of adequate signal processing techniques. Significant channel bandwidth and processing power are required, respectively, to acquire the sensor information and to perform such an analysis in a reasonable amount of time.

The impact on image quality of these types of detectors is twofold. On one hand they can be used to determine the optimum operating conditions, mainly the drop ejection energy. On the other hand, the nozzle status information, gathered by means of any of the described methods, is used to adjust the servicing and the error hiding strategies. The objective of the servicing strategies is to recover and maintain as many nozzles as possible in operating condition. Some of them are nozzle specific (spitting cycles) while others affect the whole printhead (wiping and priming). Nozzles that cannot be recovered after a reasonable effort are finally marked as unusable. The error hiding strategies allow for the implementation of fault tolerant printmodes optimized for multiple parameters (number of unusable nozzles, artifact patterns, firing frequency of the printhead, etc.). These strategies take advantage of the nozzle redundancy, either physical (created by printhead design) or logical (created by multi-pass type printmodes), to replace a failing nozzle by another that's operating correctly. At the core of the printmodes there are the masks, a data structure that, used in combination with the print data, decides for every printhead position, which nozzles will eject a drop and which ones won't. This set of masks is recalculated in response to any change in the set of failing nozzles in order to maintain the best possible image quality. The calculation is a non-trivial mathematical problem requiring a significant amount of computing power.

Media Advance Measurement Systems

The majority of inkjet printers use a roll-based mechanical system to position the printing media. Friction between the media and the drive roller(s) which is kept at the desired level by means of any combination of pinch wheel structures, vacuum chambers and/or back-tension modules, ensures the transmission of the advance force from the motor to the media. Almost all of the implementations currently in the market use a closed-loop system requiring a way to measure the magnitude of the advance that is subsequently fed back to the servo system in order to achieve precise media positioning.

Optical encoders are commonly used to sense the media position. This encoder is directly attached to some of the mechanical parts forming the media advance subsystem (typically the drive roller or the motor axis) thus giving to an indirect measurement of the media movement. The different tolerances of the mechanical parts translate into measurement errors. In order to correct for these errors, several calibration techniques have been developed. They usually consist of printing a pattern at known roller positions. The pattern is subsequently measured by means of some sort of optical sensor. The error information obtained through this analysis is stored as part of the calibration information of the specific unit and is used by the servo system for every media advance movement. A careful design of the pattern is required to isolate the advance errors from the printhead errors, i.e. nozzle to nozzle trajectory variation. The same care needs to be applied to avoid the degradation of the accuracy caused by some media related defects, mainly the media expansion after printing. These calibration techniques allow for compensation of most of the repeatable mechanical errors like the average roll diameter and its variation with the rotated angle (eccentricity and higher order effects). In the case of an encoder attached to the motor axis, the transmission inaccuracies can also be calibrated.

The initial calibration of the unit is usually performed at the manufacturing line and involves specifically designed optomechanical tools. In some cases, a recalibration may be required after a service intervention. Several possibilities exist. The simplest one is a visual calibration consisting of printing several calibration patterns that are inspected by the customer in order to inform the system about the one he or she considers the best. An alternative technique requires the portion of media containing the calibration pattern to be loaded again in the suitable orientation in order to be scanned and analyzed by means of the same sensors used for dot placement error.

Increased requirements in terms of resolution, throughput and swath height have posed additional pressure to design higher resolution, more accurate media advance systems. Bigger encoder discs, or higher resolution ones, have demonstrated difficult to integrate and manufacture. In many printers the classical encoder with digital outputs has been replaced by an analog encoder sensor. By sampling the two quadrature analog signals (either a sinusoidal or a round edge triangular signal), and without changing the encoder disk, it is possible to increase the resolution by a factor that typically ranges from 8 to 64 times. Besides the increased complexity of the processing electronics, this solution requires additional calibrations of the encoder subsystem. Both the mechanical tolerances (warp and eccentricity) of the disc assembly and the dependence of the output signal with rotational speed, aging of the optical devices, ink aerosol deposition, can appear as measurement errors that translate into image quality degradation. The results of the calibration cycles, executed either at printer startup or at certain time intervals, are used to tune up the encoder subsystem (electronics and algorithms) in order to maintain the desired accuracy along the printer life.

All of the previous indirect measurement systems suffer from accuracy degradation if media slippage occurs (relative movement between the media and the drive roller). An accurate mechanical design and the use of reasonable acceleration and deceleration values during the media advance movements allow keeping the slippage at a minimum. The remaining slippage error is usually characterized by means of the so-called slippage factor and treated as an additional calibration factor.

An indication of the interest in this research field is given by some new proposals based on direct media measurements, and intended to solve the drawbacks of previous systems. Possibly the simplest one consists of an encoder driven by the media, usually by means of some sort of tracking wheel. This concept has been implemented in the Zünd UV-Jet 215 printer. A design ensuring that no slippage occurs between the media and the tracking wheel (something, otherwise, non trivial), combined with the right servo system, would allow for very accurate media positioning. Such a design shares some of the requirements of the conventional encoder systems in terms of calibrations, i.e. for effective diameter, eccentricity.

A completely different media tracking system has been proposed in some relatively recent patent applications[10]. It is based on two image sensors that take images of the media and that are spaced apart a known distance *d* in the advance direction. An image of a certain media region is captured by the first sensor. An image of this media region is captured again by the second sensor when the region is in its field of view. Both images are compared to compute an offset, that jointly with the distance *d* provide very accurate displacement information. Either inherent or artificially induced media features are captured by the image sensor. To our knowledge, as of today there is no commercial application of this technique.

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Biographies

Ramon Borrell received his Masters degree in Industrial Engineering from the Universitat Politècnica de Catalunya in 1987 and a Master on Automotive Industry from Universitat Politècnica de Catalunya in 1993. Since 1994 he has worked in Inkjet Commercial Division at Hewlett-Packard in Sant Cugat del Vallès, Spain. His work has primarily focused on the development of inkjet-based writing systems for wide format printers, including print modes, pipeline algorithms and color and image quality issues. Since 2000 he has focused on product architecture and technology roadmaps. He is a member of IS&T.

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