Print Quality Test Page

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A print quality (PQ) test page is a diagnostic tool which is designed for accurate and effcient diagnosis of PQ defects. We develop a set of test pages for the customer to check the condition of a printer without using any other tools. We design test features which clearly reveal the common PQ defects that occur with color laser printers, such as failure of color plane registration, ghosting, and repetitive artifacts. We then incorporate these test features into a set of test pages for a specific print mechanism architecture. We introduce the concept of imperfections within specification which are PQ defects that fall within the PQ specification of the printer. The PQ test pages should be designed to not reveal such defects to the customer. For the constant tone fields on the test page, we consider the specific case of designing halftone patterns that will not show fine pitch banding that is within specification. Finally, we describe the design of a set of instruction pages that walk the customer through the process of identifying on the test pages PQ defects that can be remedied by customer replaceable parts.

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Introduction

An important class of print quality (PQ) defects of laser printers are artifacts that degrade the quality of printed images, due to the electrophotographic (EP) process and associated print mechanism. Some common forms of such PQ defects are randomly scattered dots or smudges, repetitive patterns, and density variation in constant tone areas. For a color laser printer, poor color plane registration and temporal color inconsistency are also considered to be PQ defects. The aforementioned defects can be caused either by the non-ideal characteristics of the print mechanism and EP process, or by physical damage to a printer component. Some defects may disappear after several prints. For example, foreign matter may become attached to a roller and then later be removed in the course of normal printing. As another example, rollers that sit under pressure may develop a flat spot at the point of contact while the printer is idle. After continued use, the flat spot gradually disappears. However, a permanently damaged unit may continue to be a source of defective prints, and will need to be replaced.

A customer who finds a PQ defect on a print may consult the user manual to identify the cause of the problem. If the problem persists, the customer can call the customer support center to ask for help in diagnosing the problem. For several reasons, it is, however, diffcult for agents in the customer support center to identify a defect over the phone. The agent obviously does not have first hand knowledge of what the PQ defect looks like on the printed page. Also, there may be discrepancies between the technical lexicon used by the customer and that used by the agent.[1] Remote diagnosis is made all the more diffcult because defects may look different depending on the image content. When there are problems with remote defect diagnosis, the surest way to eliminate confusion and identify the defect is to have the customer send in samples of prints with the PQ defect, or to dispatch a service technician to the customer site. These solutions are costly to both the customer and the printer manufacturer.

PQ defect diagnosis can proceed more effciently with the aid of a PQ test page, which is based on prior knowledge of the defects for a particular printer, such as the spatial patterns of the defects. Once a defect is noticed in a print, the customer prints the test page from the defective printer and calls the customer support center. Since the agent is already familiar with the test page, the customer need only describe the symptoms of the defect without explaining what is the image content. In addition, the customer can solve some problems by referring to the user manual or instruction pages, which contain sample defects shown on the test page, and which suggest how to solve the problem causing each defect. Therefore, the PQ test page can increase effciency in identifying PQ problems, and decrease the cost of customer support and service.

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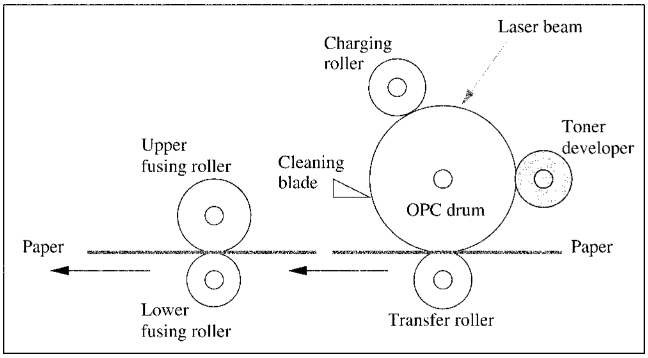


Figure 1. A common architecture of an EP laser print mechanism

It is the purpose of this paper to show how to design a set of PQ test pages for a color laser printer. In addition, we describe an accompanying set of instruction pages, which are a tool for self-diagnosis and remedying the cause of the PQ defects. The rest of the paper is organized as follows. In the **Electrophotographic (EP) Process** section, we briefiy describe the EP process with a common architecture for the laser print mechanism. Then in the **Print Quality Defects** section, we discuss the PQ defects which are frequently observed with color laser printers. In the **Strategy for Designing Test Pages** section, a strategy for design of PQ test pages is presented. The basic features in the PQ test pages that we have developed are then described in the **Test Features in the PQ Test Pages** section. Finally, we talk about how to use the PQ test pages for defect diagnosis in the **Utilization and Implementation of PQ Test Pages** section. We also describe how we implemented the PQ test pages in this section.

Electrophotographic (EP) Process

We design a test page for PQ defect diagnosis to identify the cause of the defect by interpreting the appearance of the defect on the test page. This appearance is determined by the defective unit in the EP process of the print mechanism. In order to design a test page in such a way that the PQ defect is effciently and easily interpreted, it is important for a test page designer to understand the EP process and the basic architecture of the print mechanism. In this section, we briefly describe the EP process in the context of a common architecture for the print mechanism. A detailed discussion of the physics can be found in Ref. 2.

Figure 1 shows the cross section of the print mechanism for a typical monochrome laser printer. The major components of the EP process are an OPC drum, a charging roller, a toner developer, a transfer roller, and a fuser. Each of these subsystems rotates at an appropriate speed in the printing process.

The EP process involves six distinct steps[2] as described below. In the first step, the charging roller charges the surface of the OPC drum. Ideally, the OPC drum should have a uniform potential over its entire surface. Here we assume that the drum is negatively charged. The second step is the laser beam exposure. When the laser beam scans the surface of the OPC drum, it decreases the negative potential on the exposed areas. Since the image, electrostatically formed at this stage, is not visible to the human eye, it is called the latent image. In the third step, negatively charged toner particles on the developer roller are attracted to the surface of the OPC drum. Due to the electric field created by the charge on the OPC drum, the toner particles are attracted to the latent image, which is the area exposed to the laser beam. In the fourth step, the paper is fed between the OPC drum and the transfer roller. Then the transfer roller charges the back of the paper with positive charge which is opposite to that of the toner on the OPC drum. Consequently, the toner on the OPC drum is transferred to the paper. Since the toner placed on the paper during the transfer process adheres to the paper electrostatically, it can easily be smeared by even a light touch. The fuser melts the toner onto the paper to create a permanent image in the fifth step. The upper fusing roller is negatively charged so that it can repel toner particles and prevent them from adhering to the roller. In the final step, the cleaning blade removes the residual toner particles on the OPC drum, preparing for the formation of the next image.

As described above, the monochrome printer has an architecture to produce one plane of a color page. In a color printer, this architecture is extended to generate multiple color planes. The characteristics of some PQ defects of a color laser printer are essentially the same as those of a monochrome printer. However, there are some PQ defects which are unique to the color printing process. For example, the failure of color plane registration is a PQ defect appearing only in a color printer. In the section **Strategy for Designing Test Pages**, we discuss color laser printers and illustrate one specific printer model for which we have developed a set of PQ test pages.

Print Quality Defects

In this section, we will discuss the PQ defects which are common in color laser printers. These defects can be categorized into three groups: 1) defects of uniformity, 2) random marks or repetitive artifacts, and 3) color defects.[3] The defects in the first group produce visible density variations that appear as fine pitch banding or streaks in constant tone areas. The second group has two different types: one is random and the other is repetitive. The former has the appearance of randomly distributed marks or artifacts, while the latter shows repetitive marks with a fixed interval. The defects of the first and second groups are very likely to be characterized by their spatial features such as localized marks or fine pitch banding that occurs throughout the page. However, the defects in the third group lack distinctive spatial features. Instead, these defects show color problems caused by one or more color planes, or by interaction between those planes.

We will explain the causes of the PQ defects and illustrate them with examples from scanned defective prints. We will also describe the condition that makes each defect more clearly visible to the human viewer. In this paper, we will use the letters C, M, Y, and K to denote the colors of cyan, magenta, yellow, and black, respectively.

Defects of Uniformity

The defects of uniformity are print artifacts that are easily noticed in nominally uniform areas. Fine pitch banding and streaks are the well-known defects belonging to this group.

Fine pitch banding is one of the defects of uniformity,[4] appearing as tightly spaced lines that are most visible in constant tone areas as shown in Fig. 2. In a laser printer, a laser beam is scanned across the surface of

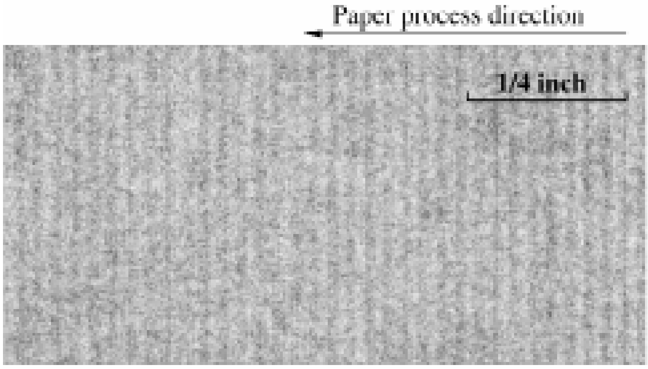


Figure 2. Scanned sample of fine ptich banding artifact induced by OPC drum velocity variation. The artifact consists of the evenly spaced vertical lines.

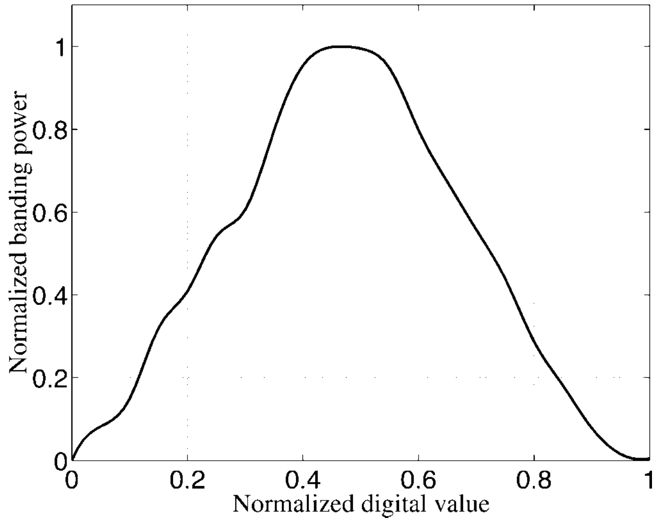


Figure 3. Measurement of tone dependency of fine pitch banding. Here the normalized digital values of 0 and 1 corresponds to white and black, respectively.

an OPC drum in the direction perpendicular to the motion of the OPC drum. Due to gear noise, the angular velocity of the OPC drum fluctuates in a quasiperiodic manner. This fluctuation causes the raster lines on the OPC drum to be unevenly spaced.[5,6] These raster position errors result in variation of the density of the toner which is perceived as fine pitch banding.

Fine pitch banding is primarily visible in halftone areas of the print, and its strength depends on both the type of halftoning texture and the average gray level associated with the halftone. We previously studied the tone dependency of fine pitch banding for a typical halftoning method, and used the result in a process for simulating fine pitch banding.[3] This dependency is shown in Fig. 3, where for each of 20 absorptance levels, the banding power was integrated over the frequency range which is associated with the fine pitch banding. We note that the fine pitch banding is strongest in the midtones. In light tone (low digital value) areas, there is not as much toner to make the drum position errors visible. Also dark tone (high digital value) areas show less modulation than the midtone areas because most of the paper is covered by toner which masks the position errors, decreasing the severity of fine pitch banding. This result also corresponds to the observation of human viewers, so that fine pitch banding is generally more visible in the midtone areas than other areas.[7]

The streak defect is another defect of uniformity[8–10] that is as easily observed in constant tone areas as is fine pitch banding. However, the appearance of the streak defect is different from that of fine pitch banding. While fine pitch banding appears as tightly packed quasiperiodic lines perpendicular to the paper process direction, the streak defect consists of wide and irregular lines in the paper process direction as shown in Fig. 4. Streaks are caused by non-uniform development and transfer of toner particles during the printing process, resulting in density variation along the scan direction.

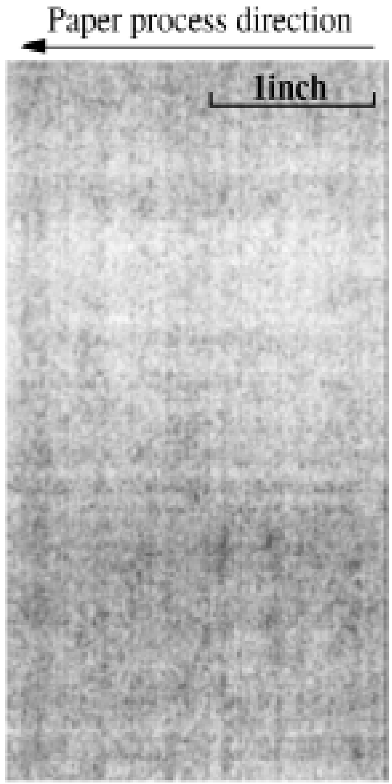


Figure 4. Scanned sample of streak defect. The artifact is exemplified by the irregularly spaced horizontal lines. Note that this sample also contains vertical line defects which may be characterized as low frequency banding.

Random Marks or Repetitive Artifacts

While the defects of the first group may be distributed over the entire page, the defects belonging to the second group are rather localized. For some of them, the defect marks are randomly scattered across the page. Others appear in a repetitive pattern. Here we will discuss scattered spots, repetitive artifacts, and ghosting defects.

There are two types of scattered spots. One consists of white specks, and the other consists of color spots. The former is caused by foreign matter that is dispersed and becomes attached to the OPC drum. Toner particles cannot develop at these positions. As a result, scattered small white specks appear on the print, which are particularly visible in areas of high toner coverage. On the other hand, color spots may be caused by poor sealing of a toner cartridge, allowing toner to spill out onto the printer components or media. The result is randomly scattered color spots or blobs. These spots can appear

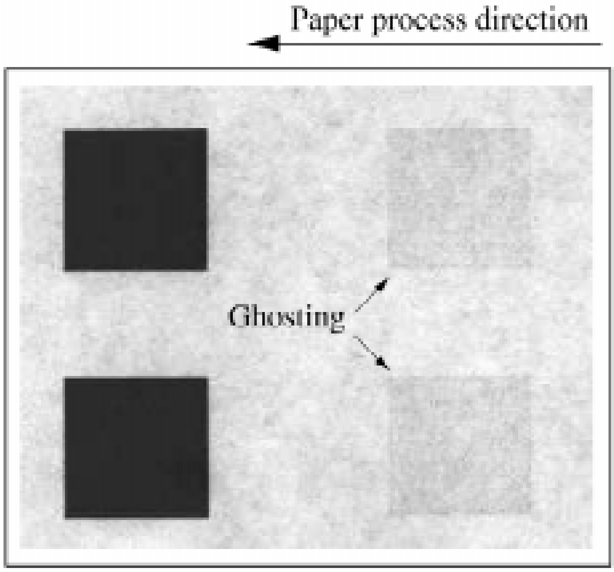


Figure 5. Scanned sample of ghosting defect.

outside the printable area of the page or even on the back of a page that has been printed on one side only.

A repetitive artifact is a PQ defect which has a pattern that reappears on the printed page at regular intervals. It results from physical damage to or contamination of a rotating unit such as a charging roller, an OPC drum, or a fuser. Depending on the contaminated unit and the cause of the damage, the symptoms of the repetitive defects are diverse. The charging roller, for instance, can generate two distinct types of repetitive artifacts: one is a repetitive spot pattern, and the other is a repetitive line pattern. Unwanted substances, such as paper dust, may adhere to the surface of the charging roller, so that the corresponding positions on the OPC drum are not charged. This results in unwanted toner developing and finally transferring onto the paper, thereby showing repetitive spots on the print.

On the other hand, a repetitive line pattern is generated by the flattened surface of the charging roller. If the printer has been turned off for a long time, the area in contact with the OPC drum will be flattened. As a result, the charging level of this area is different from that of other areas. Since the area of contact consists of a narrow band along the length of the charging roller, the repetitive pattern is a band along the scan direction. The period of a repetitive defect is generally the same as the circumference of the defective unit. Therefore, the source of the repetitive artifact can usually be identified by measuring the distance between two consecutive defective marks.

Ghosting is a PQ defect which looks like a repetitive artifact showing vestigial objects at an interval as shown in Fig. 5. The cause of ghosting is residual toner particles that remain on the OPC drum or the fuser.[11,12] If a cleaning unit does not work properly, toner particles from an object printed near the leading edge (in the process direction) of the page that did not originally transfer to the media or transfer belt may transfer to the media or transfer belt during a subsequent revolution of the OPC drum, causing a ghost image to appear on the page. This ghost image is displaced in the process direction from the original object by a distance equal to one or more times the circumference of the defective printer unit. Therefore, this distance is also a key piece of diagnostic information as is the case with repetitive artifacts.

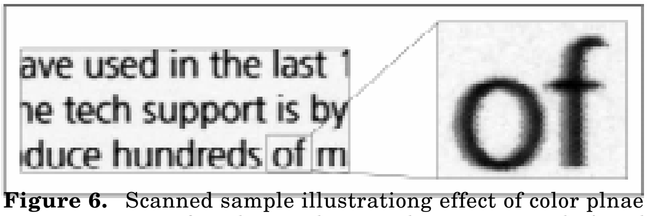


Figure 6. Scanned sample illustrationg effect of color plnae mis-registration. *Supplemental Material—Figure 6 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

Color Defects

The third group of defects consists of problems with color reproduction. The two most important defects in this group are failure of the color plane registration (CPR) and lack of color consistency. Since the color separations in a color laser printer are sequentially developed directly onto the paper or onto an intermediate transfer unit and then transferred to the paper, the accuracy with which different color planes are placed on top of each other is a key issue in a color printing system. Poor registration of multiple color planes can result in an image which looks out of focus. Text consisting of two or more primary color planes may seem to have a halo around it, as shown in Fig. 6. Problems with color consistency manifest themselves as a change in the appearance of colors specified by the same digital values either within a single page or across multiple pages. This can be caused by a defective charging or developing unit. Sometimes environmental factors, such as temperature or humidity, may contribute to the problem. In an extreme case of this problem, one color plane is not developed at all over the entire page. We refer to this artifact as the missing color problem.

Strategy for Designing Test Pages

Since the PQ test pages are expected to benefit the customer as well as the printer manufacturer, the test page designer should consider the needs of both sides. One key criterion in designing PQ test pages is ease of interpretation. Several problems may arise if the test page is complicated. The customer might call the customer support center without even trying to solve the problem. It will also be diffcult for the customer support center agent to diagnose the problem over the phone because it will be diffcult to explain to the customer how to use the PQ test page. Failure to diagnose the problem remotely may require that a technician be dispatched on-site which will increase the cost of support.

From the manufacturer's perspective, it is important that the PQ test pages not reveal artifacts that may occur when the printer is functioning within specification, and which would probably not be noticed in the content that the customer routinely generates with the printer. We refer to artifacts of this type as *imperfections within specification*. Fine pitch banding is a good example of such an artifact since it is generally characteristic of laser printers. For a specific printer model, the level of fine pitch banding is determined by the design of the printer mechanism, and usually cannot be reduced by adjusting the parameters of the device or by replacing parts. Therefore, the designer should plan the test page in such a way that the customer will not discern imper-

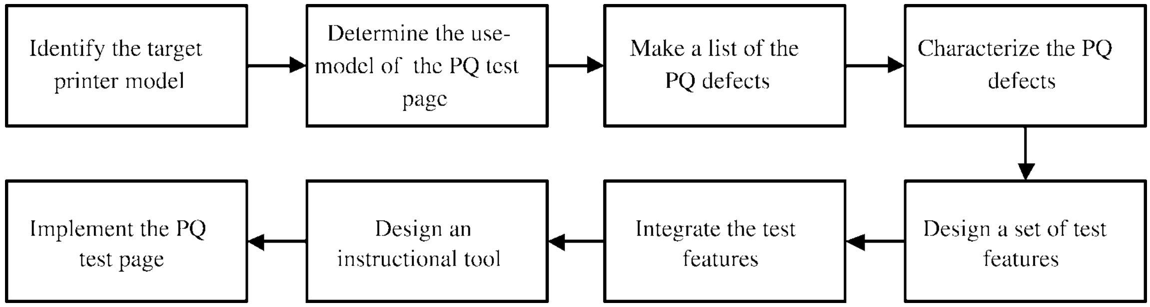


Figure 7. Flowchart of the general procedure for design of PQ test pages. *Supplemental Material—Figure 8 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

fections within specification, but will be able to clearly recognize the artifacts caused by a defective printer unit.

In the following two subsections, we will discuss a design procedure for a general printer architecture. Then we will briefly describe a specific printer architecture for which we have developed a set of PQ test pages.

General Procedure for Design of the PQ Test Pages

In this subsection, we discuss the general procedure for design of the PQ test pages as shown in Fig. 7.

1. The test page designer identifies the printer model for which a suite of PQ test pages is to be developed. The architecture of a printer model directly relates to the cause and the appearance of each PQ defect. Therefore, it is important for the designer to be well aware of the print mechanism of the printer model to develop an eficient set of test pages which clearly reveals the PQ defects.
2. The designer determines the use-model of the PQ test page. There are two different modes for use of PQ test pages. One is a remote diagnosis in which the customer solves a PQ problem over the phone with the aid of an agent in the customer support center. The other is the customer's self-diagnosis with an appropriate instructional tool which describes how to diagnose the PQ defects by using the test page.
3. The designer makes a list of PQ defects which are to be diagnosed by using the test page. In this step, the designer prioritizes the PQ defects and determines which defects should be addressed and inserted in the defect list. A key factor in the defect-prioritizing process is the frequency of occurrence for each defect. This data can be based on the results of internal testing of the printer or on the PQ defects reported by customers if the printer has already been introduced in the marketplace. In addition, the designer should assess the level of diffculty to resolve a certain PQ problem, and consider it in designing a test page with regard to the use-model. We can classify a PQ defect into one of the following groups: 1) fixable by the customer alone, 2) fixable by the customer with the guidance of an agent in the customer support center, 3) fixable by a technician dispatched to the customer's site, and 4) not fixable at all.
4. Once the list of PQ defects is determined, the designer characterizes each defect based on its causes and the physical appearance, and identifies the conditions under which the defect is clearly visible.
5. Knowing the characterization of the PQ defects, the designer can devise test features which make the defects clearly visible. At the same time, the design parameters should be carefully controlled so as to not show any artifact caused by an imperfection within specification. The designer should develop each test feature so that the customer can easily interpret it.
6. The designer incorporates the test features into a set of PQ test pages for the targeted printer model. The test features should be logically and clearly organized so that there is no ambiguity in interpreting the test page. Otherwise, the test pages may confuse the customer, resulting in an incorrect diagnosis. Additionally, it is important that the test features be compactly integrated to minimize the number of test pages that need to be printed. The customer may be reluctant to take the time to print many test pages, and may not wish to use his or her consumables to do so. In fact, the customer may resent having to do this if the PQ problem is viewed as being the manufacturer's fault.
7. The designer develops an instructional tool which illustrates how to use the PQ test pages. The instruction pages can be stored in the firmware of the printer, printable along with the test pages from the front panel control menu. Or an instructional tool can be included in the manufacture's website.
8. The final step of the design procedure is to implement the developed test pages and instructional tool. The implementation should take into account the convenience of printing and the storage limitation for the test page and instructional tool. The storage requirements can be minimized by choosing an appropriate file format and design method. In our work, we used the PostScript™ file format and the vector graphic drawing method, which we describe in the **Utilization and Implementation of PQ Test Pages** section.

In-Line Printer Architecture

The two major classes of color EP printer architectures are in-line and multipass. Within each of these classes, there are a number of variations. Although some PQ defects are generally characteristic of the EP process, the specific appearance of these defects may depend on the printer architecture and EP process behavior for each particular printer model. Other PQ defects may be unique to a specific printer model. In this paper, we will show how to design a set of PQ test pages for the in-line printer mechanism architecture, which is illustrated in Fig. 8. The in-line printer has four different imaging stations. Each station has an OPC drum, a charging roller, a laser scanner unit, and a toner developer. A transfer belt transports the paper sheet between these stations. In the final stage of the printing process, a fuser melts toner particles onto the paper to create a permanent image. In this article, we assume that the media is Letter-sized (or A4-sized) and that it is fed to the printer long edge first. Thus, the process

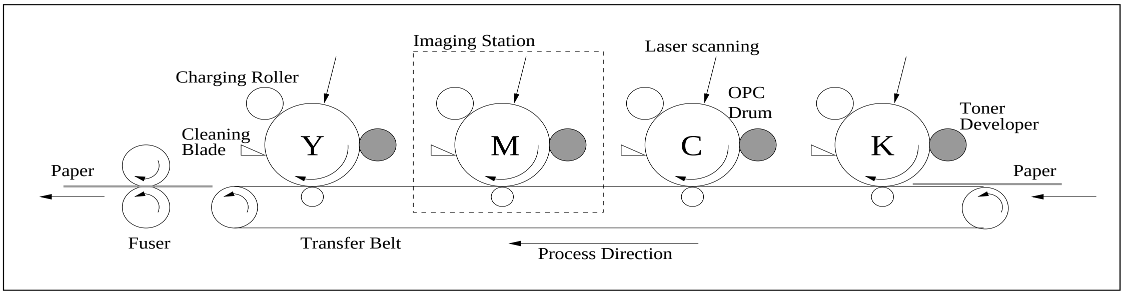


Figure 8. In-line color EP print mechanism. There is a separate imaging station for each of the four color separations. Each imaging station consists of an OPC drum, a charging roller, a laser scanner unit, a toner developer, and a cleaning blade. The paper is transported past each imaging station by the transfer belt. After all four color separations are transferred to the paper, it passes between a heated fuser roller and a pressure roller to fuse the toner to the paper.

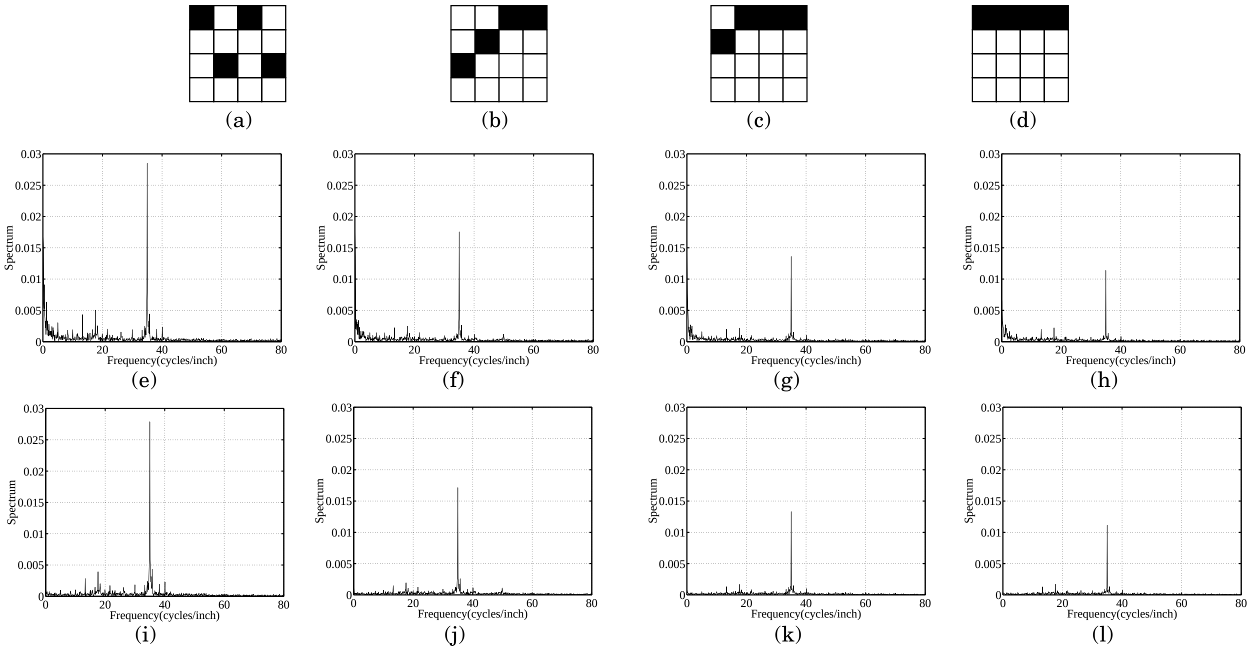


Figure 9. Four halftone patterns (1st row) and the corresponding spectra of projected profiles of constant tone patches. The velocity modulation of the OPC drum results in the high peaks at 35 *cycles/in* in the spectra unweighted (2nd row) and weighted (3rd row) by the contrast sensitivity function of the human viewer at 12 inches viewing distance.

direction is along the short edge of the media; and the scan direction is along the long edge.

Test Features in the PQ Test Pages

In this section, we will show how to develop test features to make the defects clearly visible. When we develop the test feature for a given defect, we should consider the condition under which the defect and its cause are clearly identified. The basic features that we will discuss are a constant tone background which is divided into sections, ghosting test blocks, rulers, color plane registration (CPR) test blocks, and page identification numbers. Finally, we will show how to incorporate the test features into a set of PQ test pages for a color laser EP printer.

Constant Tone Background

A PQ test page should be designed to clearly show defects that the manufacturer considers to be out of specification and which the customer can remedy by replacing a consumer-replaceable part, or which should be reported to the customer support center. With the exception of the CPR problem, PQ defects are generally most visible in areas of the print that consist of a constant tint fill. Thus we will use a constant tone background, on which other test features will be built. If we use four different constant tone images, each of which contains only one of the four primary colors, we can separately check the condition of each imaging station. For example, if white streaks are found in the magenta constant tone image, the magenta imaging station can be suspected as being defective.

Although a constant tone image clearly shows PQ defects such as scattered spots or repetitive artifacts, it may also reveal fine pitch banding that might not be visible in the content normally printed by the customer. Thus fine pitch banding is considered to be an artifact caused by imperfection within specification; and it should be concealed in the test page. In order to find a halftone pattern for the background that can effectively conceal the fine pitch banding, we next examine the strength of fine pitch banding for four different halftone patterns.

Figure 9 compares the spectra of the projected absorptance[6] of four halftone patterns with a 4×4 period for a

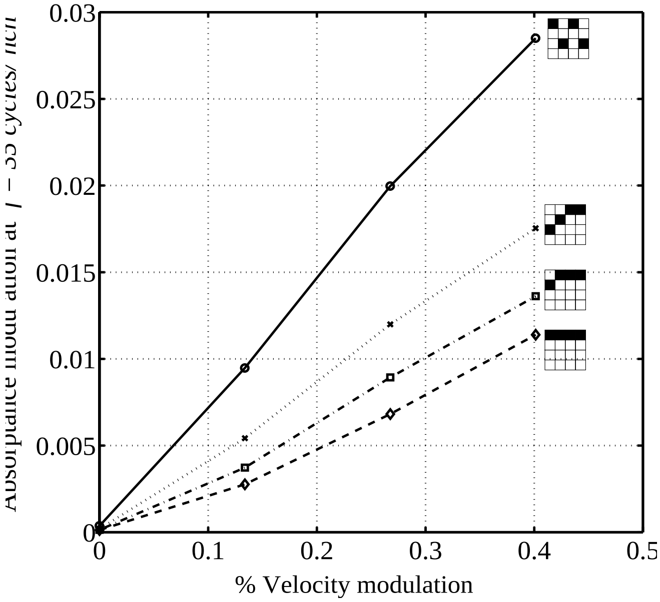


Figure 10. Absorptance modulation versus velocity modulation. A dispersed dot halftone pattern tends to be more sensitive to the velocity modulation of the OPC drum than a line halftone pattern. *Supplemental Material—Figure 10 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

fixed number of dots (4 dots out of 16 pixels) in each period. These patterns are shown in Figs. 9 (a)-(d). We printed constant tone patches with these halftone patterns at 600 dpi using an HP color LaserJet 4500. In order to test the robustness of the halftone patterns to fine pitch banding, we modulated the speed of the motor that drives the OPC drum[13] and measured the spectra of the projected absorptance profiles. The modulation was sinusoidal with frequency f_{mod} = 35 cycles/in. Figures 9 (e)-(h) show the spectra of the printed samples generated by these halftone patterns. To better illustrate the visual significance of these result, we also show the spectra weighted by contrast sensitivity function by the human viewer for a viewing distance 12 in.[14] We observe that the amplitude of the frequency peak at f_{mod} decreases as the dispersed dots are gradually rearranged to form lines in the process direction. This means that a dot pattern is more sensitive to the velocity fluctuation of the OPC drum than is a line pattern under a given condition of the printer engine, thereby showing more severe fine pitch banding.

Figure 10 is a plot of absorptance modulation versus velocity modulation, where the absorptance modulation is the amplitude measured at f_{mod} and the velocity modulation is the amplitude of the motor speed modulation divided by the nominal velocity. Overall, the absorptance modulation increases as the velocity modulation increases. Also this figure shows that fine pitch banding is more severe in the constant tone area with a dot screen halftone pattern than with a line screen halftone pattern. This is because the dots form lines along the paper process direction that effectively mask the dot position errors, thereby reducing the severity of fine pitch banding. For this reason, we use a line screen halftone for the background of the test page.

In order to choose the screen frequency and line width for the line screen halftone, the test page designer should keep in mind that these parameters determine the density level of the constant tone background, which is a key factor to clearly show PQ defects. Some defects such as repetitive color dots and ghosting artifacts are more visible against a lighter background, while other defects such as scattered white specks are more easily noticed on a darker background. Therefore, the designer should carefully choose the screen parameters to yield an appropriate level of density with which the various types of PQ defects can be effectively diagnosed. In our study, we used a line screen frequency of 120 lines/in. and a 20% fill. At a printer resolution of 600 dpi, we thus print a line in one column of pixels out of five.

Ghosting Test Block

When a drum is not thoroughly cleaned, the residual toner particles are transferred onto the paper, causing a ghosting defect. The heavier the density of the image content, the more residual toner particles remain, showing a darker ghosting image. Since those residual toner particles are transferred after one revolution of the drum, the ghosting image can appear on the same page as the original object that provided the source of the toner, if the source object is located near the leading edge of the paper and the circumference of the drum is less than the width of the paper. Let δ be the circumference of the drum, W the width of the paper, w_g the width of the test bar, and m the margin on each side of the test page. Then provided $\delta < W - (w_g + 2m)$ the test bar located at the leading edge will be reproduced on the same page by a defective drum as illustrated in Fig. 11.

The source of the ghosting artifact tends to influence the entire surface of the drum, so that the ghosting image for the test bar in Fig. 11(a) would have almost the same density along the full height of the page. Since the defect of repetitive lines which is caused by a flat spot along the length of the charging roller shows a shape similar to that of the ghosting defect in Fig. 11(a), the customer might have trouble differentiating between the two defects. This problem can be avoided by changing the shape of the ghosting test bar. For example, as shown in Fig. 11(b), the ghosting test bar can be made shorter than the height of the page; and it can be designed with a characteristic structure. Here the three tint fill blocks with varying densities can help gauge the strength of the ghosting.

Ruler

In some cases, the customer will need distance information or location information to identify the source of defects. For example, the distance between two repetitive marks is the information that identifies the source of the defective printer unit because the interval of the repetitive defect is the same as the circumference of the defective printer unit. Also, we can identify which printer unit causes a ghosting defect by measuring the distance between the ghosting test bar and the faintly reproduced ghost image. Since the location of the ghosting test bar is fixed on the test page, the ghosting caused by a particular printer unit will always occur at the same position. In other words, the customer can identify the source of the defect by examining the position where the ghost image is located on the printed test page. In this case, the customer can identify the source of the ghosting defect with location information only.

If rulers are incorporated on the PQ test page, then the customer does not need to use a separate instrument to obtain distance information or location information. We use horizontal and vertical rulers to acquire this information in both directions. We put those rulers

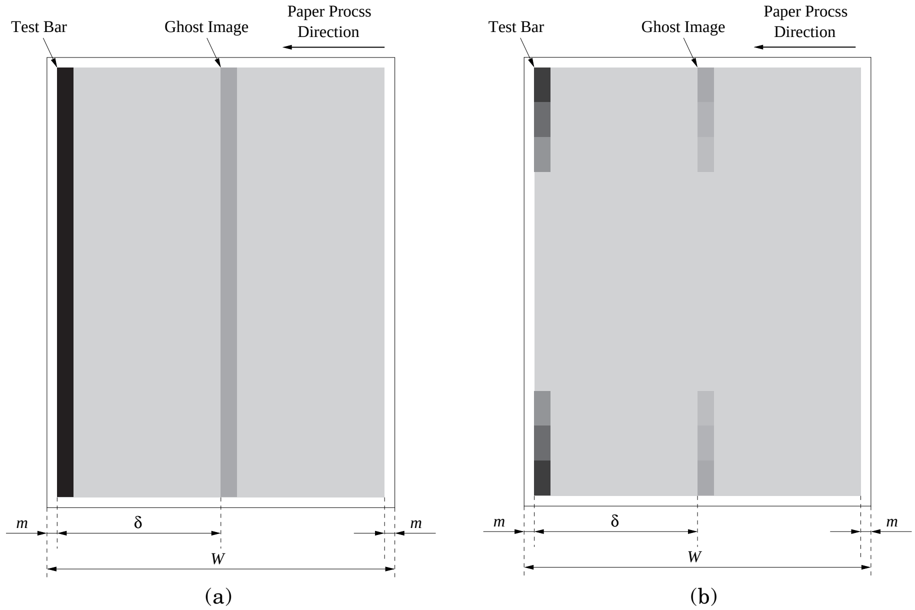


Figure 11. Features for detecting ghosting: (a) simple test bar, and (b) two test bars of three tint fill blocks with varying densities.

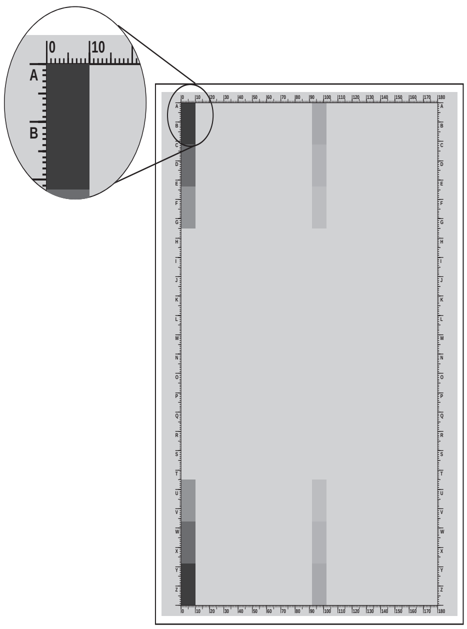


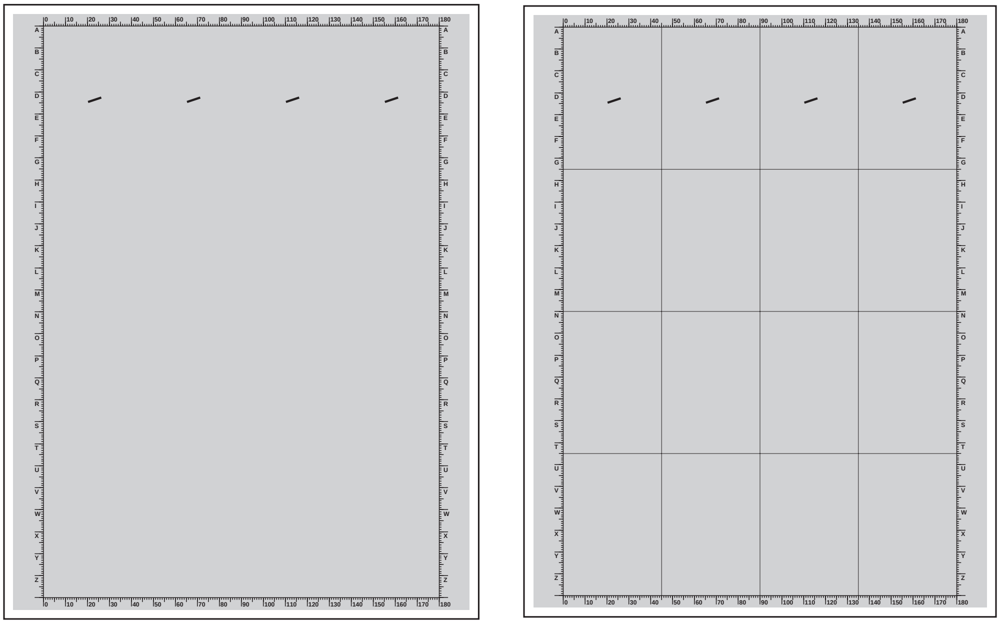
Figure 12. Ghosting defect shown on a test page which has rulers. The horizontal rulers provide the distance information to help identify the source of the ghosting defect.

on all four sides of the PQ test page as illustrated in Fig. 12. Normally, a ruler consists of evenly spaced tick marks and numbers. However, using numbers for both the horizontal and vertical rulers can be a source of confusion during communication between the customer and the agent in the remote diagnostic process. In order to avoid this potential problem, we use two different sets of characters for the horizontal and vertical rulers; one is a set of numbers, and the other is a set of alphabetical characters. Since it is more convenient to use a numeric ruler for measuring the distance between repetitive artifacts which always occur along the paper process direction (horizontal direction in our design), we use numbers for the horizontal rulers.

Divided Sections

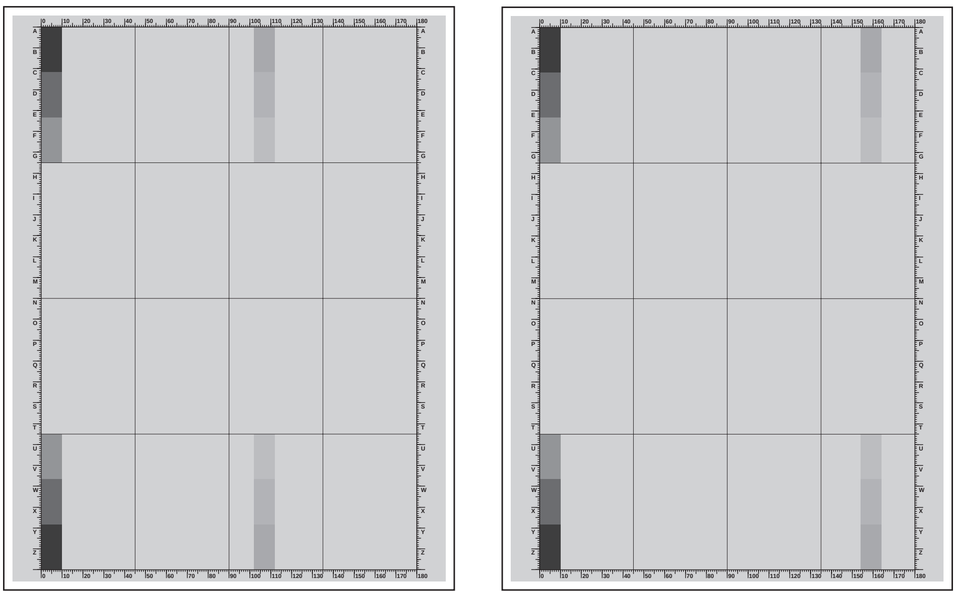
A repetitive artifact appears at a particular interval in the process direction. As previously mentioned, we can identify the source of a repetitive defect by measuring the distance between two successive defect marks. If the designer knows which repetitive defect is expected to occur most frequently, the source of the defect can be identified by evenly dividing the test page in the process direction into sections whose width is the same as the interval of the defect. Then the customer just needs to check whether the defect marks occur at the same horizontal position in each section of the test page. Although this information could be obtained by using the rulers at the top and bottom of the page, the sections allow the customer to identify the targeted repetitive defect at a glance without the need to make measurements with rulers. For example, repetitive marks caused by the magenta charging roller (circumference 45 mm) are illustrated on a test page containing rulers only (Fig. 13(a)) and on a test page containing rulers and divided sections (Fig. 13(b)). In order to identify the defect on the test page of Fig. 13(a), the interval of the repetitive marks must be measured with the horizontal rulers. On the other hand, the fact that the defective mark appears at the same position in each divided section as shown in Fig. 13(b) indicate that the source of the defect is the magenta charging roller.

In a similar way, the sections can provide location information that can be used to identify the cause of a PQ defect. For example, if there are two different printer components which cause ghosting defects; and the difference between the circumferences of these two components is greater than the width of one section, then the ghosting images would appear in different columns, as shown in Fig. 14. Here the source of the ghosting defect can be identified by simply referring to the column number without using a ruler to get exact position information.



(a) (b)

Figure 13. Repetitive marks caused by the magenta charging roller (circumference 45mm). (a) To identify the defect, the interval of the repetitive marks must be measured with the horizontal rulers. (b) Here, the fact that the defective mark appears at the same position in each divided section indicates that the source of the defect is the magenta charging roller.



(a) (b)

Figure 14. The ghosting defect can be attributed to one of two possible sources by identifying the column in which the ghost occurs. (a) Ghosting defect shown in the third column, and (b) ghosting defect shown in the fourth column.

Test Block for Color Plane Registration (CPR)

Levien developed a registration mark by overprinting two screened patches which have slightly different screen frequencies showing a moire pattern.[15] Misregistration in any direction results in a moire pattern that is different from that observed when the screens are properly registered. He also designed marks which use a line pattern showing misregistration in either the vertical or horizontal direction.

We develop a test feature for color plane registration that uses overlapping line patterns to assess how much a color plane is displaced. Figure 15(a) shows a series of test units identified by numbers ranging from –5 to 5. Each unit contains several horizontal lines, and is divided into two parts. The left half consists of black lines only, and the right half has both black lines and magenta lines. Except for the unit 0, the magenta lines in the right part of each unit are deliberately displaced by $n\Delta$, where n is an integer and Δ is the increment of displacement. If there is no CPR problem, the magenta lines in unit 0 will be completely covered by the black lines so that the left and right parts of each unit will

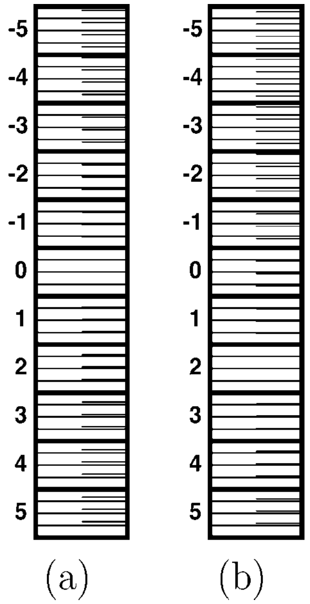


Figure 15. CPR test block designed for testing the vertical registration of the magenta plane relative to the black plane. (Lines in the black plane of the test patttern extend fully across the frame; lines in the magenta plane extend half-way across the frame from the right edge) (a) Without any vertical CPR problem, the left and right parts of unit 0 match each other. (b) The magenta plane is vertically shifted so that the two parts in unit 0 no longer match. Instead, the left and right parts in unit 2 look the same, thereby indicating there is a CPR problem, and the magnitude of the misregistration is 2Δ, where Δ is the amount by which the magenta bars are vertically displaced from unit to unit on the right side of each unit. *Supplemental Material—Figure 15 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

match. The right part of each other unit shows an increasing hue difference from the left part, as the unit index increases or decreases.

If the magenta plane is vertically shifted relative to the black plane, the left and right parts of the unit 0 will no longer match, indicating that there is a CPR problem as shown in Fig. 15(b). In this figure, the magenta plane is vertically shifted by 2Δ, so the magenta lines in the right part of unit 2 are covered by the black lines, thereby making the two parts of this unit look the same. Thus, we can tell how much a color plane is shifted by identifying the index of the test unit in which the two parts of the cell match each other most closely. If the test units are symmetrically arranged in increasing or decreasing order as in Fig. 15, the unit corresponding to correct registration of the two color planes is located in the center of the series. This arrangement makes it easy to assess the CPR performance. If the level of misregistration is not a multiple of Δ, but is $a\Delta$ where a is not an integer, we can infer the actual misregistration by identifying the two adjacent units in which the left and right parts most closely match each other. The unit indices will be $\lfloor a \rfloor$ and $\lceil a \rceil$. A CPR test block with the same structure as that shown in Fig. 15, except that the lines in each unit are rotated by 90°, can similarly be used to assess horizontal CPR.

Page Identification Number

If the PQ test page suite consists of more than one page, a page identification number facilitates communication between the customer and the agent. In choosing the color for these numbers, the designer should consider the case in which one of the primary colors is not developed so that the background for that color is missing. In this case, the page identification number can be easily used to identify which page does not show its background color. This information would be lost however, if the page identification number is printed in the same color as the background.

In order to avoid this problem, we use the secondary color that is complementary to that of the background in each page. This choice, additionally, provides good contrast thereby making these numbers easily identified.

Integration of Test Features

The suite of the PQ test pages that we have developed consists of five pages. Each page is designed to test one of the four color separations: K, C, M, and Y. The background of the last two pages is divided into two parts, which are yellow and green. The green background is comprised of yellow and cyan color separations, which is expected to show more clearly density variation in the yellow plane. Figure 16 illustrates the complete PQ test page for the M separation. The rest of the test pages are shown on the user instruction pages (Fig. 17) as iconic images. In each test page, the ghosting test blocks are located at the leading edge; and the page identification number is positioned between the two ghosting test blocks.

In order to effciently detect repetitive defects, we set the width of each section to 45 mm, based on the assumption that the repetitive artifact caused by the 45 mm circumference charging roller is the most frequently reported repetitive defect. On each test page, there are 12 sections arranged in a 4×3 array surrounded by the four rulers. The unit of the rulers is millimeters.

There are two sets of CPR test blocks which are placed at the left and right side of each test page. Each set consists of three blocks: one horizontal CPR test block is located between two vertical CPR test blocks. Since the range of misregistration in the paper process direction is generally larger than that in the scan direction, we use more levels in the horizontal CPR test block. The horizontal and vertical CPR test blocks incorporated in this test page can show horizontal misregistration up to ± 8 pixels at 600 dpi ($\approx \pm 340$ μm) and vertical misregistration up to ± 6 pixels at 600 dpi ($\approx \pm 250$ μm), respectively. The degree of misregistration of a color plane can vary throughout the page. The four vertical and two horizontal CPR test blocks can monitor this variation within each page. For the K separation page, we put CPR test blocks for the cyan and magenta planes on the left and right sides, respectively. We use a unique label for each CPR test unit to eliminate a potential source of confusion. The label consists of three parts. We use X and Y to indicate whether the test unit belongs to a block on the left or right. The second part (a, b, or c) points out whether the block is an upper, middle, or lower test block. The last part is the unit index number which indicates the level of misregistration.

Utilization and Implementation of PQ Test Pages

PQ Defect Diagnosis by Using PQ Test Pages

In this section, we describe how to use the test pages we have developed in the PQ defect diagnostic process. We consider two cases of defect diagnosis: one is a remote diagnosis, and the other is the customer's self-diagnosis.

In the case of remote PQ defect diagnosis, the customer calls the customer support center when any PQ

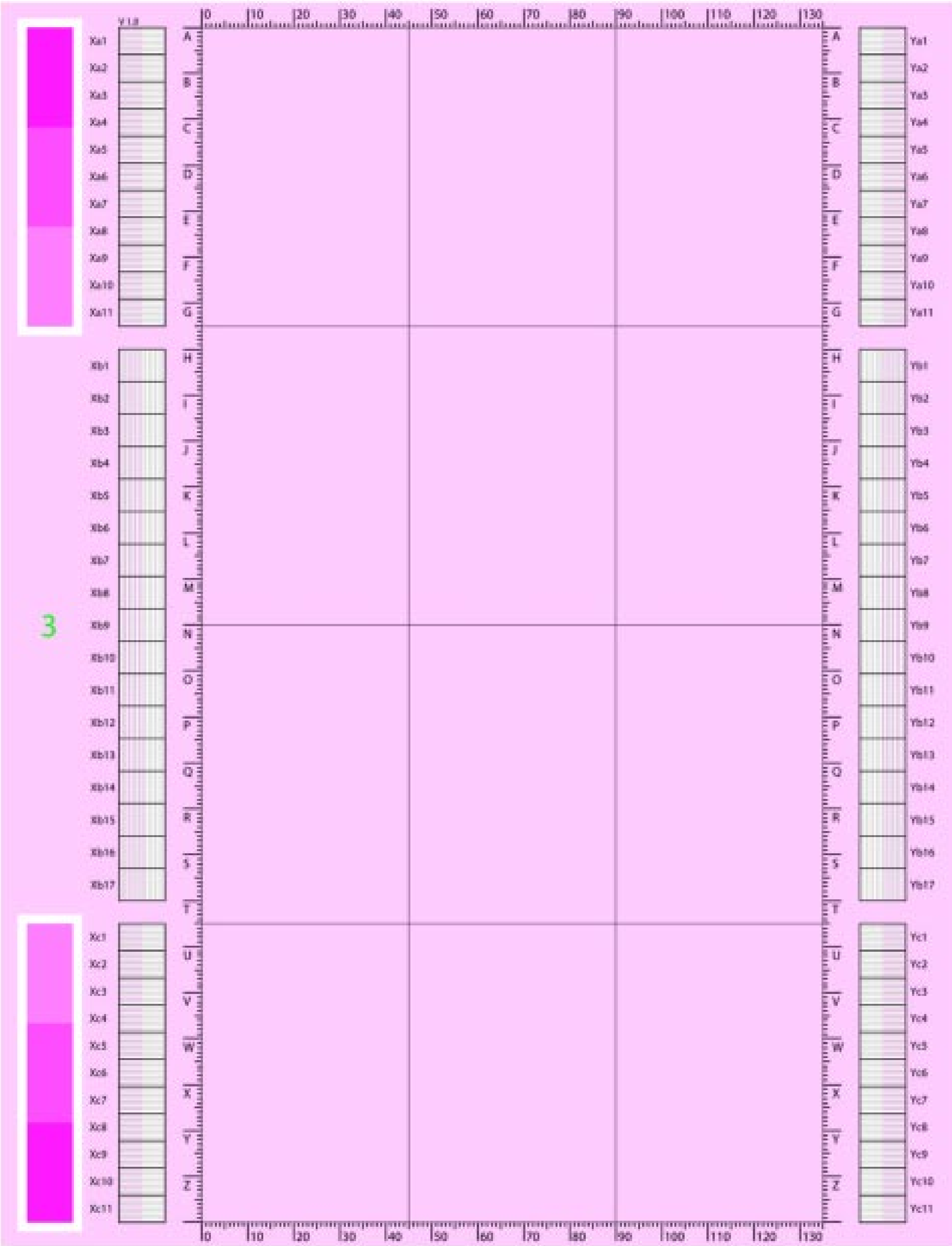
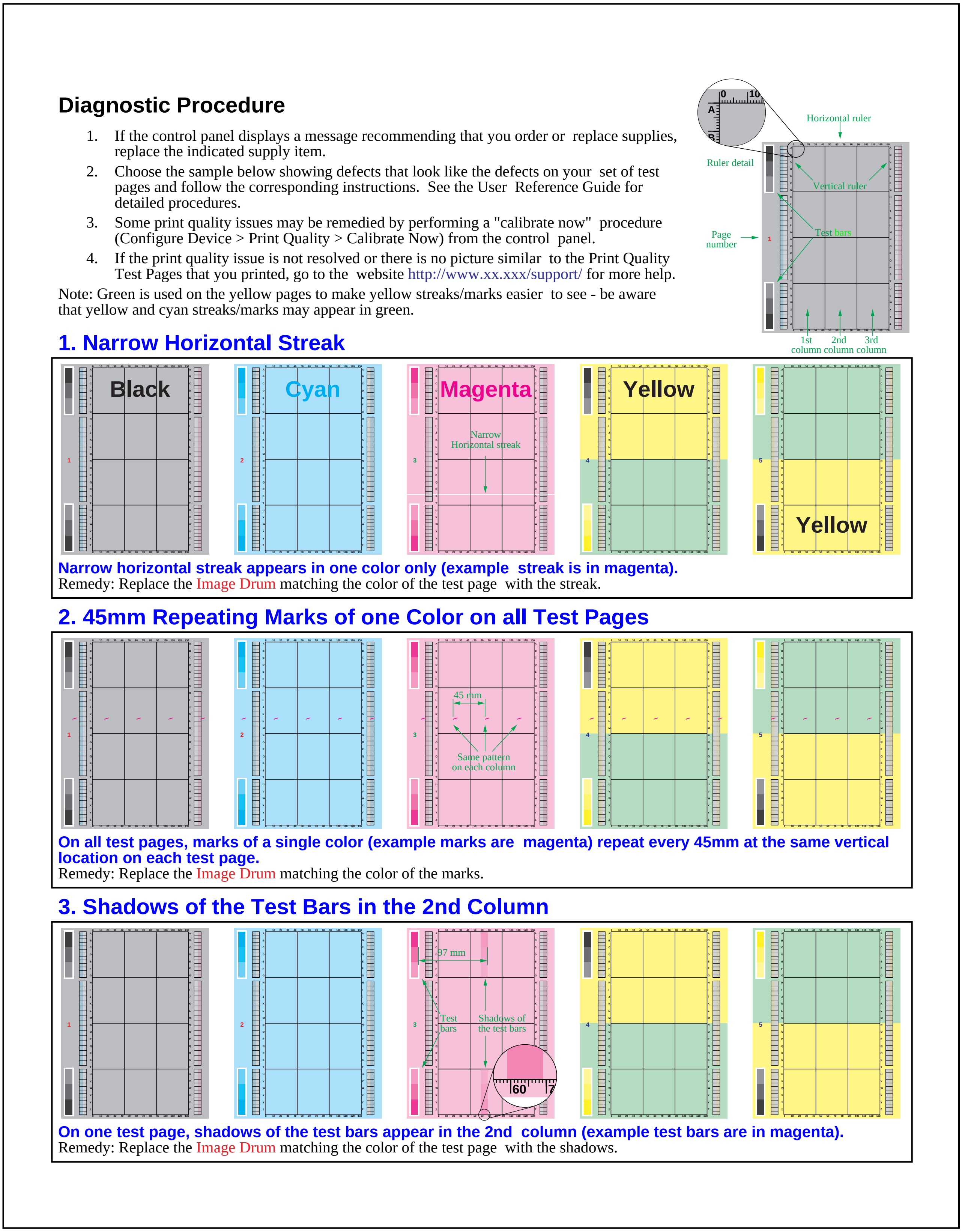


Figure 16. Complete PQ test page for the magenta color plane.



Diagnostic Procedure

1. If the control panel displays a message recommending that you order or replace supplies, replace the indicated supply item.
2. Choose the sample below showing defects that look like the defects on your set of test pages and follow the corresponding instructions. See the User Reference Guide for detailed procedures.
3. Some print quality issues may be remedied by performing a "calibrate now" procedure (Configure Device > Print Quality > Calibrate Now) from the control panel.
4. If the print quality issue is not resolved or there is no picture similar to the Print Quality Test Pages that you printed, go to the website http://www.xx.xxx/support/ for more help.

Note: Green is used on the yellow pages to make yellow streaks/marks easier to see - be aware that yellow and cyan streaks/marks may appear in green.

1. Narrow Horizontal Streak

Narrow horizontal streak appears in one color only (example streak is in magenta).
Remedy: Replace the Image Drum matching the color of the test page with the streak.

2. 45mm Repeating Marks of one Color on all Test Pages

On all test pages, marks of a single color (example marks are magenta) repeat every 45mm at the same vertical location on each test page.
Remedy: Replace the Image Drum matching the color of the marks.

3. Shadows of the Test Bars in the 2nd Column

On one test page, shadows of the test bars appear in the 2nd column (example test bars are in magenta).
Remedy: Replace the Image Drum matching the color of the test page with the shadows.

Figure 17. First page of instructions for using the PQ test pages.

problem is observed. The agent in the support center will ask the customer to print the PQ test pages and to describe any noticeable symptoms of the defect. Since the agent can be assumed to already know the symptoms of various types of PQ defects when printed on the PQ test pages, the agent can ask the customer very specific questions regarding the symptoms of the defect. For example, the agent can ask the customer to examine if there are dark shadow marks at the particular positions where ghost images would appear. If the PQ defect cannot be successfully diagnosed remotely, the agent can ask the customer to send the printed test pages to the support center for direct evaluation by the agent. Once the PQ defect and its possible causes are identified, the agent can remotely help the customer resolve the problem or send a service technician on-site. Ideally, the test pages should be stored in the printer firmware, and should be printable from the front panel control menu.

An alternative mode for taking advantage of the PQ test pages is to provide the customer with a set of instructions on the use of the PQ test pages to diagnose the most common defects that can be remedied by replacing customer-replaceable parts. These PQ instruction pages may be stored in printer firmware, and thus be printable from the front panel control menu, included in the user manual for the printer, or accessible at the manufacturer's website. In any case, the instruction pages need to be simple, clear, and straightforward to use, or the customer will just call the customer support center, rather than attempting to self-diagnose the cause of the PQ problem. The instructions need to accomplish three tasks: (1) familiarize the customer with the features of the PQ test pages and their use, (2) provide information about how the PQ defects of interest will appear on the PQ test pages, and (3) suggest a possible remedy for the PQ problem, once the defect is identified.

Figure 17 shows the first page from a set of PQ instruction pages that we designed for a particular printer. These pages exemplify the three tasks just mentioned. At the top left side of the page, there is a general description of the diagnostic procedure. To the right of this description, there is an image of the test page defining all the features and terms used in the instructions that follow. Note that the CPR test blocks are not mentioned, since for this particular printer, identification and correction of CPR problems is not something that the customer is expected to do. The remainder of the page is divided into three sections, each devoted to a different PQ defect. Each section shows images of all five PQ test pages, as they would appear in a typical occurrence of the defect. The defects are simulated on the PQ test pages using techniques described in Ref. 3. In each section, labels and dimensioning are used where appropriate to help identify the PQ defect. Below these images, the remedy for the PQ defect is briefly described. Where appropriate, the customer is directed elsewhere for more detailed information.

The instruction page shown in Fig. 17 directs the customer to the manufacturer's website for further diagnostic procedures. One could build a more interactive diagnostic tool at the website by utilizing a graphical user interface. One could develop, for example, an application which simulates a PQ defect with a variety of parameters such as the level of the defect, its color, or its location on the test pages as shown at the website. Therefore, the real-time simulation system could accurately display different cases of the PQ defect based on the customer's input. For instance, the customer whose printer shows a repetitive artifact can choose the color of the defect and its position on the test pages. As a result, the PQ problem can be more closely matched with the simulated defect so that the customer can proceed more confidently with the self-diagnostic process. Figure 18 illustrates two different cases of a repetitive artifact, one showing cyan defect marks at the top of the test page and the other showing black defect marks in the middle. This is a feature that cannot be achieved with static, printed instruction pages, in which only one case of each defect can be shown because of the very limited space. For example, Fig. 17 shows only magenta marks as a sample case of the 45 mm repetitive artifact.

However, the use of such a web-based tool for PQ defect diagnosis would require that the customer log onto a computer, go to the manufacturer's website, and then navigate through a process requiring multiple mouse-clicks and probably some text entry. For a simple defect that can be identified by inspecting the instruction pages printed directly from the printer control panel, this would be a relatively inefficient approach to resolving the customer's problem. So it may be desirable to provide the customer with various types and levels of diagnostic tools so that the PQ problem can be solved by applying tools of increasing complexity and sophistication until the correct diagnosis is made.

Implementation of PQ Test Pages and PQ Instruction Pages

When implementing the suite of PQ test pages, we should consider its file format and how it is to be printed. In our study, we developed the test page suite in the PostScript page description language which is supported by our target printer product as well as many other laser printers, and stored it in the firmware to be printable from the front control panel. We can generate a PostScript file by converting a test page in a bitmap file format in which each color plane is separately defined pixel-by-pixel. However, a simple conversion of a bitmap image to a PostScript file is not a good solution because of the large file size that results. For example, we would need about 128 M bytes for each test page defined in a CMYK bitmap format (1 byte/pixel/color) for letter-sized media to be printed at 600 dpi. Converting this test page into a PostScript file does not reduce the file size because the converted PostScript file contains the stream of image data in another bitmap format.[16] If we also need to define the test page for another page size, we have to generate it as a separate file for that specific page size, and store it in the firmware. This approach would require an unacceptable amount of memory in firmware.

Alternatively, we can generate the PQ test page suite by using a vector graphics drawing tool. Since an object in vector graphics is described mathematically rather than by a pixel-by-pixel specification, we can dramatically decrease the file size, especially for a test page to be designed at a high resolution. However, there may be a lot of redundancy in a file that describes such a suite of PQ test pages. The redundancy results from frequently repeating objects which are defined multiple times with slightly different parameters. For example, we have to generate test pages for different color planes separately despite the fact that all test features are the same except for the color. Also, each tick mark on a ruler will be individually drawn and defined with a positioning parameter if we generate the test pages by using a

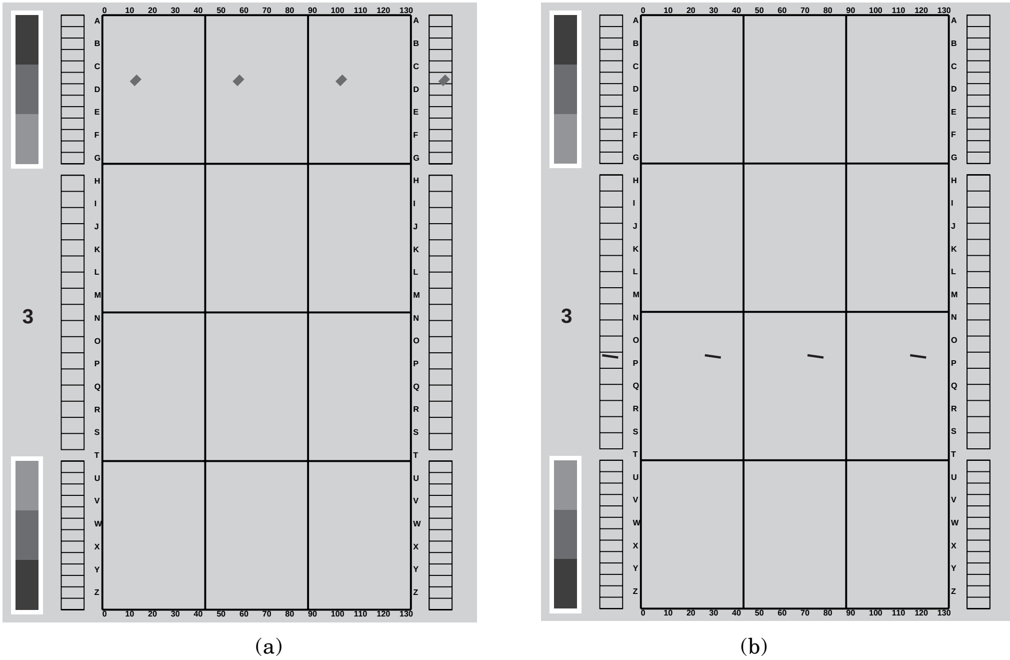


Figure 18. Simulation of repetitive defect marks caused by (a) a cyan charging roller, and (b) a black charging roller. All these cases of the repetitive artifact cannot be put in static, printed instruction pages. On the other hand, an application which can simulate PQ defects onthe manufacturer's website may make it possible for the customer to generate a simulated defect which is more closely matched with the actual PQ problem by controlling the simulation parameters, resulting in a more confident diagnosis of the PQ defects. *Supplemental Material—Figure 18 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

drawing tool. Finally, with a drawing tool we will still have to generate a separate file for each different page size supported for the test page suite.

This redundancy can be eliminated by programming the test features in vector graphics, making them into modules, and calling them as sub-routines with different parameter values whenever we need to put them on the page. For example, we coded a module for the ghosting test block with arguments specifying the position of the block and a set of color values for the three tint fill sub-blocks. We then called the module with different argument values for different pages and the different locations of the two test blocks on each page. The code that we developed also has a function that checks the current setting of the page size in the printer, and uses this information to automatically calculate the position and size of each test feature, so that we do not need to generate a separate file of test pages for each different page size. In addition, the code uses the loop control operator *for* in PostScript to repeatedly place a series of objects such as tick marks on a ruler or lines in the CPR test blocks, without defining each object individually. Using 40 Kbytes of storage, we described all five test pages in PostScript with support for Letter, Ledger, A4, and A3 media using the automatic page size switching function.

For the PQ instruction page shown in Fig. 17, we redesigned the test pages as small iconic images. Since the test pages do not show as much detail in this small size, we captured the major features of the test page and simplified them for rendering in the iconic images. As previously discussed, each section of the PQ instruction page shows all five PQ test pages with a typical occurrence of the defect. In the simulation process, the defects are rather exaggerated to be appropriately visible in the iconic images. The PQ instruction pages could be designed by using a word processor, in which each test page icon is treated as an individual object which occupies a certain amount of memory. This leads to a large amount of redundancy, thereby undesirably increasing the size of the PQ instruction page file.

We resolved this problem by also coding the PQ instruction pages in the PostScript language and following a strategy similar to that used to design the PQ test pages. In the PostScript file for the PQ instruction pages, we wrote a sub-routine that generates an iconic image of the PQ test page with a certain color for the background, ghosting test bar, and CPR test blocks. By calling this sub-routine with an arbitrary position and color, we removed the redundancy of the repeatedly placed icons. After drawing each icon, labels are added at the appropriate positions. We also made sub-routines for frequently used features such as the frame of each section and the title bar.

The PQ instruction pages were localized in five different languages: English, Spanish, French, German, and Italian. We produced a separate PostScript file for each language by replacing the text of the diagnostic procedure, defect titles, remedies, and labels on the icons. For each language, the two PQ instruction pages, which are designed to help customers diagnose seven different types of PQ defects, required 60 Kbytes of storage. The PQ instruction pages are also stored in firmware so that they are printed following the PQ test pages, whenever a customer needs to diagnose PQ defects.

Conclusion

In this article we introduced strategies and a procedure for designing a set of PQ test pages. We showed how to develop test features for the PQ defects that are common in color laser printers. We also showed how to incorporate the developed test features into a set of PQ test pages. Finally, we proposed user instruction pages which are designed to enable the customer to self-diagnose PQ problems. Although this work is focused on a specific marking process and print mechanism architecture, the design approach is quite general and could be applied to other printer systems, as well.

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