Tradeoffs Affecting Scanner Performance

A white paper by Paul M. Cashman, Director of Product Management for Scan-Optics, Inc.

1. Introduction

Comparison-shopping for a mattress is a notoriously hard consumer task, since the manufacturers go out of their way to provide a large number of proprietary and white-labeled products, all at different price points, coil counts, sizes, coverings, etc. Comparing scanners can be just as confusing, unless you know the basic tradeoffs among the key variables that determine scanner performance. This paper describes those variables and the simple arithmetic relations among them.

2. Simplified Scanner Structure

To begin with, consider the simplified structure of a scanner. A camera is positioned over a moving transport, and documents pass along the transport and go under the camera. The camera takes a picture of each document, and the resulting image is fed to an image-processing board which massages the image by removing speckles, straightening (deskewing) it, cropping the part of the image which doesn't contain the paper image, etc. The image is then output to a file for later processing, such as offline OCR.

The camera consists, at its heart, of an electronic device known as a CCD (charge-coupled device). Every CCD has a number of elements, each of which captures one pixel. As the paper passes under the camera, the CCD "fires" its elements, so each element captures one pixel across the width of the document[1]. As the transport moves the paper, the next "scan line" of the document comes under the CCD, and the CCD captures that scan line. Each scan line succeeds the previous scan line by one pixel in the length dimension. Clearly, it takes time for the CCD to fire its elements and capture a one-pixel-wide scan line. So the transport cannot move the paper too fast, or the CCD will miss some scan lines.

How fast can the transport move without causing the CCD to miss a single scan line? That depends on the optical resolution required. Suppose, for example, that the resolution required is 200 dpi. Each dot is one pixel. So the CCD must be able to make 200 sweeps across the entire width of the document in the time it takes the transport to move the document one inch farther down the track[2]. If 400 dpi resolution is required, the CCD would either have to scan twice as fast as in the 200 dpi case (at the same track speed), or the transport would have to move only half as fast (at the same CCD scan rate as in the 200 dpi case)[3].

3. Field-of-View and Optical Recognition

CCDs come in a number of different sizes. For example, IBML's Image Trak has a low-resolution camera with 2096 elements and a high-resolution camera with 4096 elements. Some CCDs have more elements than are used in actual processing. This is useful in cases where the scanner manufacturer wants to allow room for higher-resolution capture than is offered in standard models, without having to redesign the camera. Unused CCD elements do not affect the time the CCD needs to capture a scan line.

How many elements[4] are needed in a CCD? That depends on two factors, the field-of-view (FoV) and the optical resolution required.

FoV is the maximum width the CCD can "see." This is equivalent to saying that FoV is the maximum number of pixels in the width dimension that the CCD can capture in one scan line. Let's consider a CCD with 4096 elements. At 200 dpi resolution, one scan line can capture (4096 pixels)/(200 pixels per inch) = 20.48 inches of width. At 300 dpi, the same CCD can capture (4096 pixels)/(300 pixels per inch) = 13.65 inches of width. And at 400 dpi, its FoV is 10.24 inches.

Conversely, suppose we needed to capture at 400 dpi a document that is 11" wide. That means we would need a CCD with at least (400 pixels per inch) * (11 inches) = 4400 pixels (elements).

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1 For simplicity, "length" refers to the paper dimension in the direction the transport travels, and "width" refers to the paper dimension orthogonal to transport travel.

2 The CCD is physically sweeping across the width of the document. In order to capture 200 pixels in the length dimension across the entire width of the document, the CCD must make 200 sweeps, where each sweep is 1 pixel wide in the length dimension and (200 * document width) pixels in the width dimension.

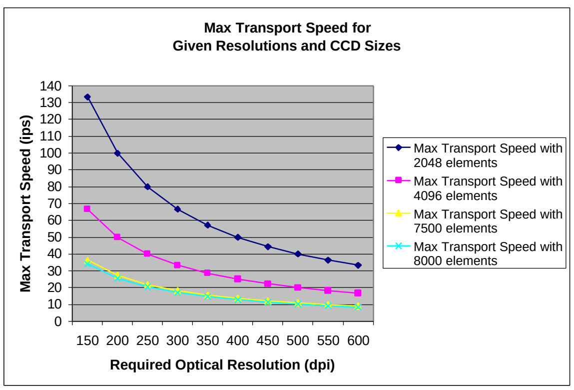
3 This analysis ignores the processing speed of the image-processing board. That will be brought up in section 7.

4 Unless otherwise noted, "CCD elements" should always be taken to mean elements actually used to capture a scan line. Unused elements do not enter into it.

So we can sum this up as:

> **<u>Equation 1</u>**: FoV = Number of CCD elements/Optical resolution
>
> Or alternatively: Optical resolution = Number of CCD elements/FoV

The graph below shows the maximum optical resolutions possible, given different sizes of CCDs and different fields-of-view. Clearly, the bigger the CCD (i.e., the more elements used), the greater resolution is possible at any given FoV. But this will have an effect on transport speed, as we will see in the next section. There is no free lunch.



4. CCD Elements and Transport Speed

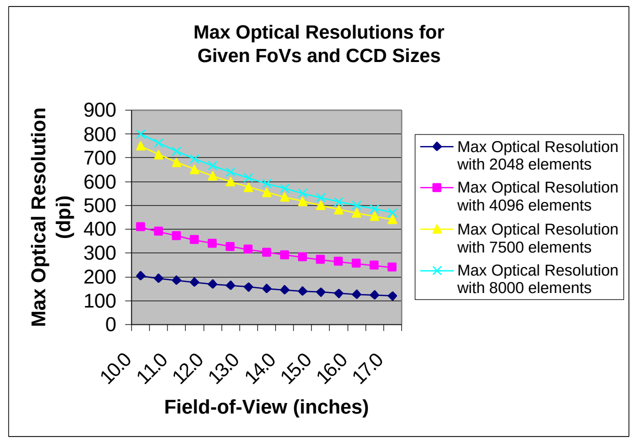
Now that we have the relationship between FoV, optical resolution, and number of CCD elements, we can go back to the question in section 2, namely, how fast can the transport run?

Suppose we have a 7500-element CCD and when we use only 4096 elements, the CCD is capable of performing 10,000 scans/second. (This is a consequence of its circuitry, and is not related to any other factors we've been discussing.) Let us also assume that 4096 elements give us a sufficient FoV at the resolutions we're interested in.

If 200 dpi resolution is required, then the maximum transport speed is (10,000 scans per second)/(200 scans per inch) = 50 inches per second (ips). Note that we've changed "200 dpi" to "200 scans per inch". This is because we're talking about speed in the length dimension: before the transport can move to the next scan line, the CCD has to complete one full scan in the width dimension. So to get 200 dpi in the length dimension, it has to make 200 scans per inch. We can sum this up as:

> **<u>Equation 2</u>**: Maximum transport speed = CCD scan rate/resolution

The following chart shows the maximum transport speed possible, given various CCD sizes and required optical resolutions (assuming the CCD can do 10,000 scan lines per second with 4096 elements in use). Clearly, as more CCD elements come into use, the maximum transport speed goes down (this is the subject of Equation 3 below).



If 400 dpi resolution is required, then the maximum transport speed is (10,000 scans per second)/(400 scans per inch) = 25 inches per second (ips). This assumes that the 10.24" FoV is sufficient for the application. But what if it isn't?

Let's suppose that we need to capture documents up to 12.8" wide at 400 dpi. That means (using Equation 1) that we need a CCD with 12.8 * 400 = 5120 elements. Since we have a CCD with 7500 elements available, that CCD will work. But how many scan lines per second can it generate? If 4096 elements can be run at 10,000 scans/second, then 5120 elements can be run at (4096/5120) * 10,000 scans/second = 8000 scans/second. Then at 400 dpi, the transport speed (using Equation 2) will be 8000/400 = 20 ips. We can express this as:

> **<u>Equation 3</u>**: CCD scan rate using Y elements = CCD scan rate using X elements * (X/Y)

5. Tradeoffs Among The Key Variables

Equations 1, 2, and 3 express an important set of design tradeoffs for the scanner. Once the FoV and maximum optical resolution is set for the scanner by its designers, these determine the number of CCD elements needed, which in turn determines the scan rate and therefore the maximum transport speed for different optical resolutions required by scanner applications. If the scanner is required to scan wide documents at high resolution, it means that the maximum transport speed at *any* resolution will be slower (at the corresponding resolution) than if the scanner were designed to scan narrower documents at the same or lower maximum resolution.

We can see this by a simple example. Consider two scanners, A and B, with the following characteristics:

	Scanner A	Scanner B
FoV (inches)	12.8	10.24
Max optical resolution (dpi)	400	400
CCD elements used (Eq. 1)	5,120	4,096
CCD scan rate at 4096 elements (lines/sec)	10,000	10,000
CCD scan rate for # used elements (Eq. 3)	8,000	10,000
Max transport speed at 200 dpi (Eq. 2) (ips)	40	50
Max transport speed at 300 dpi (Eq. 2) (ips)	26.67	33.33
Max transport speed at 400 dpi (Eq. 2) (ips)	20	25

The maximum transport speed for Scanner A is slower across the board than Scanner B. However, Scanner A can scan wider documents at higher resolution than B.

6. Optical resolution vs. scalable resolution

Most scanner specifications list the optical resolution (sometimes called the base resolution) and also the scalable resolution. Scaling is done by the image processing board (IPB), and means that each pixel captured by the CCD is mathematically combined with its neighbors to yield either more or fewer pixels, depending on whether the image is being scaled up or down. For example, an image captured at 200 dpi can be scaled up to yield an image at 400 dpi. Each pixel in the original captured image becomes two pixels in the output image. The IPB determines the values of these generated pixels by examining the values of neighboring pixels and inferring what the "missing" pixel values should be.

This is one way to get a 400 dpi image (to stay with this example). The other way is to use a camera with 400 dpi optical resolution. The image quality of the latter will be superior, since it is a faithful rendition of what is on the page, without the need for any mathematical inferencing. However, as we saw in section 5, designing a scanner to capture images optically at 400 dpi would cause it to run more slowly than a scanner designed to capture images at lower resolutions and scale them up (all other design parameters being equal). So we have another tradeoff: throughput vs. image quality.

7. The image processing board

Scaling, along with other transformations to improve image quality, takes place in the IPB. The IPB's processing capacity may further constrain throughput, and may prevent the transport from running at its maximum speed as derived from the equations above.

The raw data rate coming into the IPB is:

> **<u>Equation 4</u>**: Data rate into the IPB = FoV * resolution * CCD scan rate * bytes per pixel

In units, this is:

> Bytes per second = inches * pixels per inch * (1/second) * bytes per pixel

Commonly, the result is divided by one million and expressed as megabytes per second.

The number of bytes per pixel is a design parameter of the scanner, and depends on the type of standard being used and the type of camera (color or grayscale). If the image is color, then the JPEG standard requires three bytes to represent one pixel (one byte each for the red, green, and blue color values). If the image is grayscale, then one byte is sufficient to represent 256 shades of gray ranging from pure white to pure black.

The raw data rate is reduced by operations such as sampling and cropping. The arithmetic of the IPB is not complicated, but it is tedious, and will not be given here. The resulting data rate is subject to the IPB's overall constraint, namely, that the data rate (after the raw data rate is reduced) cannot be greater than the rated capacity of the IPB to process it. If it is, the scanner will not perform to its image-processing specifications. Therefore, the transport must be slowed down to a point where the resulting data rate can be processed by the IPB without overwhelming it. At lower resolutions, this constraint may have no effect: the IPB can keep up with the incoming data rate while the transport is running at its maximum speed to capture that images at that resolution. It is at higher resolutions that the constraint may operate.

8. Summary

Designing a scanner involves making a series of tradeoffs among interrelated variables: field-of-view (maximum width of document to be scanned), maximum optical resolution (how fine-grained the scan must be), number of CCD elements, transport speed, and IPB processing rate. It is important to keep these tradeoffs in mind when comparing specifications of scanner performance or setting requirements for scanner design.

Part of what drives tradeoffs among these variables is the encompassing tradeoff between throughput and image quality. Images captured at optical resolution are better than ones which have been captured at a lower resolution and scaled up, but the value of this tradeoff can only be quantified in the customer's environment.

Scan-Optics, Inc. is a leader in applying technology to high-speed imaging, recognition, data capture, and archive and retrieval solutions. The growth of the Company's product line and the diversification of its services since its incorporation in 1968 reflects Scan-Optics' ability to respond with innovation and technical expertise to the rapidly changing business requirements of its customers. Scan-Optics' ability to offer customized and integrated system solutions has helped companies all over the world meet their productivity and profitability objectives. Offices and service representatives to support Scan-Optics products are located throughout the United States, and supplemented worldwide by select distributors in over forty countries.

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