MARK SCANNING EQUIPMENT

As computer technology rapidly propelled us into the information age, it has become evident that the bottleneck of information exchange is the interface between the human operators and their computers. Barcodes and two-dimensional codes are technologies that help to ease this bottleneck.

Barcodes are the zebra-striped patterns that one sees on product packaging in retail environments. Far beyond retail points-of-sale, barcodes are also widely used in many industrial applications including manufacturing process control, inventory control, transportation, identification, and blood banks. Two-dimensional codes (2-D codes, sometimes referred to as 2-D barcodes) are extensions of barcodes, carrying more information in the same printed area. Although most people have seen barcodes, only a select few may know the intricacies of barcodes and barcode scanning.

There are many ways through which a computer can output information for human consumption: Display it on a screen, print it on paper, or even synthesize it into voice. All of these methods are simple, accurate, and relatively fast. To input data into a computer is a different matter. Often a keyboard is used, but it is slow and inaccurate. Optical character recognition (OCR) (see Optical character recognition—OCR) for print and handwriting is becoming more sophisticated, but is still not accurate enough for most business applications. It has been realized that in many situations the information to be input into the computer is printed, and the same printing process can produce information in two ways at the same time, one for machine reading and one for human reading. Barcodes and barcode scanners are simply the marks for machine reading and the readers that read these marks.

A barcode records a short string of text, and usually it is used as the index value that represents an item in a database. Figure 1 illustrates a system employing barcode scanners as input devices. Processing a barcoded item involves a barcode scanner decoding the barcode and transmitting the result to a terminal, which requests information with this index value from a main computer hosting the database, which in turn looks up the requested information and transmits the result back to the terminal. The whole process usually takes a small fraction of a second and appears to be instantaneous.

In the following sections, after a brief historical overview, we will discuss first barcodes, followed by barcode scanners, 2-D codes, and, finally, 2-D code capable scanners.

HISTORICAL OVERVIEW

The first US patent related to barcodes was issued in 1949 to J. Woodland and B. Silver (1). Interestingly, the patent did not cover a *bar* code, but rather a *ring* code [see Fig. 2(a)]. Reportedly, Woodland and Silver first thought of using bars of different thickness to record information as well, but then decided to make the code isotropic. By bending the bars into concentric circles, the ring code looks the same from all directions, and the scanner does not have to be lined up with the code to be scanned. While not of much commercial significance, the work of Woodland and Silver demonstrated that one of the most important design criteria for a machine-readable code is the ease with which the code can be scanned.

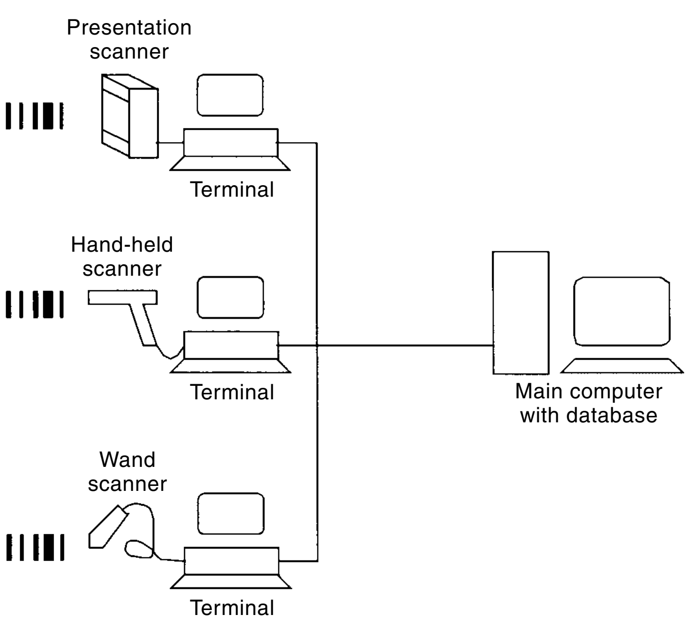

Figure 1. A system employing barcode scanners as one of its input means. Terminals, using index values encoded in barcodes, request information from the main computer hosting the database. Different types of barcode scanners can be mixed in the same application.

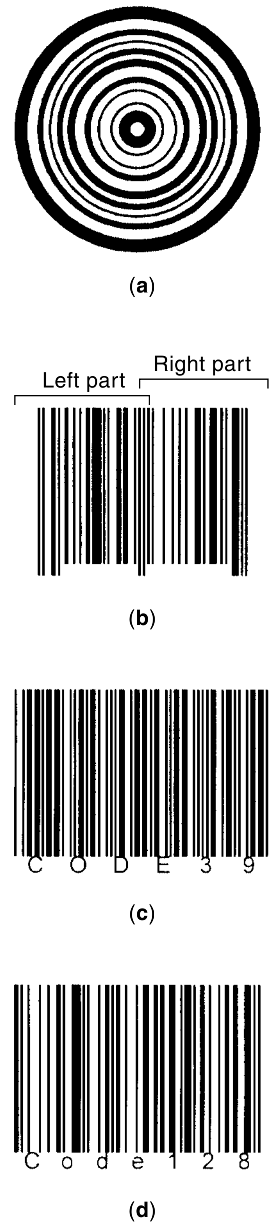

Figure 2. Examples of ring code and barcodes: a ring code illustration (no ring code standard exists today) (a), a UPC (b), a Code 39 (c) and a Code 128 (d) barcode. In (b), the UPC code is composed of two separately decodable parts, with each part being taller than wide. The start and stop patterns, as well as the center guard bars (the shared bars between the two parts), are usually extended as shown. All these measures help to ensure that a scan line misaligned at up to 45° can still cross all bars in each part completely.

Indeed, the barcode scanning equipment which best demonstrates the possible productivity gain brought about by this technology could not have been invented in the time of the Woodland and Silver patent. As we shall discuss below, only two categories of scanners (i.e., laser scanners and imaging scanners) can generate many scan lines per second and thus demonstrate the highest possible throughput that barcode technology can offer. While lasers were invented in the early 1960s, the most popular electronic imager, the charge coupled device (CCD), was invented in the early 1970s. It is little wonder that barcode applications did not emerge until the late 1960s.

The earliest successful large-scale implementation of barcodes is probably the Universal Product Code [UPC, shown in Fig. 2(b)] (2), the type of barcode currently used in supermarkets in the United States. A superset of UPC is the European Article Numbering code (EAN), which, despite the origin of its name, is now a standard adopted worldwide. Outside of supermarkets, different types of barcodes are also used by transportation, warehousing, healthcare, and other industrial sectors. The most widely used types, other than UPC/EAN, are Code 39 and Code 128 [Fig. 2(c) and 2(d)]. Each type of barcode is formed under different rules, which define different *symbologies.* A symbology is standardized in at least two ways: a standard-setting organization accepts and maintains its specification, while an industry association coordinates which symbology to use and precisely how it should be used in the particular applications pertaining to that industry. A list of organizations that participate in barcode standardization is included in Appendix A of Ref. 1.

Today barcodes are used in more and more applications in industrial, governmental, and educational institutions. By using barcodes, repetitive labor is reduced, and so is error rate, while productivity is enhanced and more data become available for real-time tracking, analysis, and control. Barcode printing and reading represents a multibillion dollar industry. The use of 2-D codes opens up even more new opportunities to applications where the input of data into computers can be automated.

BARCODES

In this section, we will first explore how information is recorded in barcodes, and then we will cover the mathematical methods utilized in barcode design.

Barcode Fundamentals

Barcodes carry their information in the relative widths of their elements (bars and spaces). Most symbologies use both the bars and spaces between the bars to record information. A barcode scanner takes samples along a line (the *scan line*) crossing all elements, measuring their widths, and decodes from the measurement the recorded message. Since no information is carried in the exact value of the element widths, a barcode can be printed at any magnification (within the capability of the printer and the intended scanner) and read at any distance.

UPC/EAN barcodes record fixed-length numerical values only. Other types of barcodes may record both numbers and letters, or even the complete ASCII code, and may also record variable-length messages. For example, Code 39, one of the most widely used symbologies, can encode all digits, all uppercase English letters, and a few punctuation marks, and it can encode variable-length messages.

Compared to ring codes, barcodes are not isotropic, but they are shift-invariant, in the sense that two parallel scanlines crossing it completely are certain to get the same information. Furthermore, barcodes are angle-insensitive. A slanted scan through a barcode yields a longer sequence of data, and possibly an electrical signal that is less well-defined, but all transitions recorded in the barcode are reflected in precise proportion. The maximum scanning angle is simply given by

$$|\theta| \le \tan^{-1} H/W \tag{1}$$

where H and W are the width and height of the complete barcode, respectively. In many applications, this angular misalignment allowance is sufficient.

In some applications it is desirable that a barcode be read regardless of its orientation. Although a *barcode* is not *isotropic,* a *barcode scanning system* can be *omnidirectional.* To construct an omnidirectional barcode scanning system using line-scanning technology, a star pattern of N or more evenly distributed scan lines can be used, where

$$N = \left\lceil \frac{\pi}{2 \cdot \tan^{-1} H/W} \right\rceil \tag{2}$$

For example, an original omnidirectional design of UPC barcode system includes a UPC barcode as presently used, along with a laser-scanner with two scan lines perpendicular to each other. The UPC barcode can be decoded in parts (the most common UPC code has two parts that share a few endbars, as shown in Fig. 2(b); and for each part, $H > W$ (referred to as *over-square*). Thus for $N = 2$, it is guaranteed that one of the scan lines can pass through each part of the barcode completely, in a direction that crosses all the bars [Fig. 3(a)].

Barcode Design Considerations

The barcode being scanned is not ideal, nor is the scanning process. The main factors affecting the performance of a barcode scanner are *signal distortion* and *noise,* both of which we will elaborate on later. To facilitate accurate decoding, barcode symbology designs employ mathematical tools to make the symbology less sensitive to signal distortion and to noise.

Generally, a character (from the alphabet for the particular symbology) is recorded as a fixed number of bars and spaces, and its recorded version is called a *codeword.* Usually in a given barcode symbology a codeword also has a fixed total width. For example, in UPC/EAN every digit is represented by two bars and two spaces taking up the total width of seven times the width of the narrowest bar (the *X dimension,* or simply the *X*). When scanned, the barcode so designed shows a marked periodicity in the electronic signal: Every codeword is represented by one cycle, consisting the same number of peaks and valleys and taking up the same amount of time. This periodicity is designed for ease of decoding. Once a periodicity is detected in a scan line, the decoder can identify which symbology is used. Different codewords are also separated by the periodicity. Symbologies that exhibit this periodicity are said to be *self-clocking.*

Common barcode symbologies are categorized according to the number of element widths allowed. Some allow only two widths for the bars and spaces, thus they are commonly referred to as *binary* barcode symbologies (or binary codes). In these barcodes, a wide element is typically more than twice as wide as a narrow element, so they can remain distinct even with some distortion and noise. Other barcode symbologies encode the information with more allowable width values (usually more than 3) and are sometimes referred to as *delta* barcode symbologies (or delta codes); the origin of the word

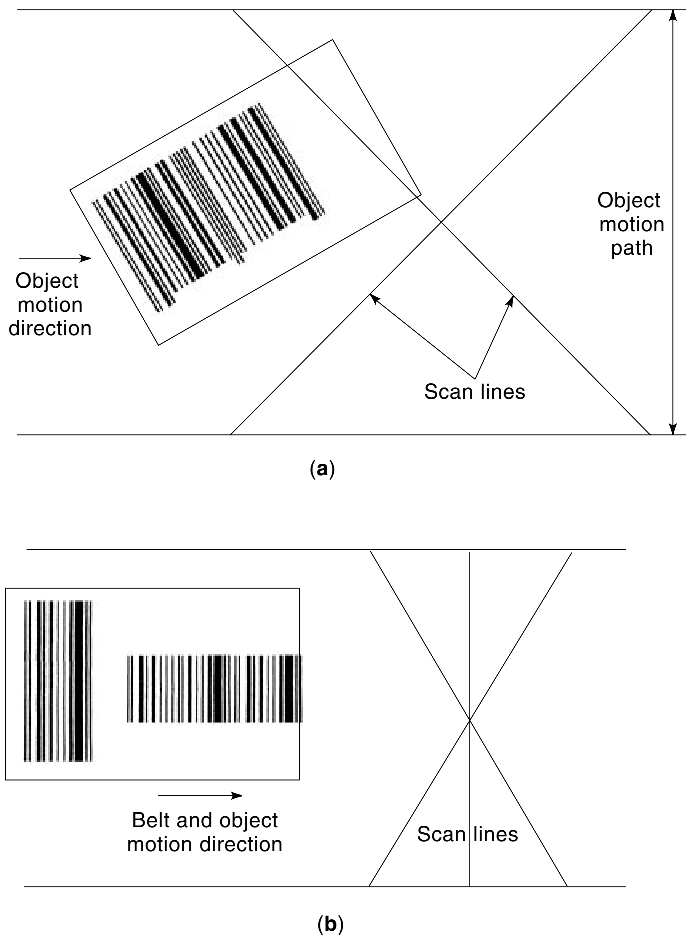

Figure 3. Two omnidirectional barcode scanning systems: (a) A UPC scanner with two crossed scan lines, each at 45° from the object motion direction and both extending across the complete motion path, and an over-square UPC barcode. (b) An overhead scanner with three scan lines (at 30° from each other) and a package bearing two identical and perpendicular barcodes.

delta is that the different widths are usually integer multiples of X. Table 1 lists the characteristics of several common barcodes, including binary codes and delta codes. The statistics shown in the table are calculated with the formula given below.

The maximum number of distinct codewords of a symbology and the recorded information density are discussed in Ref. 3. A binary code with e elements (bars and spaces) per codeword, out of which w are wide, can be referred to as a w/e code. The maximum number of distinct codewords is given by

$$S_B(e, w) = \binom{e}{w} \tag{3}$$

and the related information density is

$$H_B(e, w) = \frac{1}{[e + (r-1)w]} \log_2 S_B(e, w) \quad \text{bits}/X \tag{4}$$

where r is the ratio of the wide elements' width to that of the narrow elements. In many cases a smaller number of codewords is used, and the achieved information density is less than calculated here.

A delta code is called an (n, k) code if each codeword is nX wide and contains k pairs of bars and spaces. For example, UPC/EAN is a (7, 2) code. The maximum number of distinct codewords in an (n, k) code is given by

$$S_D(n, k) = \binom{n-1}{2k-1} \tag{5}$$

and the related information density, is

$$H_D(n, k) = \frac{1}{n} \log_2 S_D(n, k) \quad \text{bits}/X \tag{6}$$

For any n, maximum H_D is achieved by *symmetric* codes, which obey

$$n = 4k - 1$$

and

$$H_D\left(n, \frac{n+1}{4}\right) \approx 1 - \frac{\log_2[2\pi(n-1)]}{2n} \quad \text{bits}/X \tag{7}$$

Thus it can be seen that the larger the value n is, the larger the maximum H_D becomes. The trade-off is that the larger n value means a longer self-clocking period and therefore higher susceptibility to scan speed variations.

Sometimes the codewords with very wide elements are eliminated from an (n, k) code. An (n, k, m) code is the subset of an (n, k) code where no codeword has an element wider

Table 1. Characteristics of Several Symbologies Which Have Matching Ideal Models

Name	Code Type	S	H	Comment
Interleaved 2 of 5[a]	2/5	10	0.415	Codewords are interleaved: each codeword carrying information in bars is interleaved with another carrying information in spaces.
Code 39[a]	3/9	84	0.474	Intercodeword gap does not carry information.
UPC/EAN	(7, 2)	20	0.617	Only 10 distinct codewords are used in UPC-A, the most popular subtype of UPC.
Code 93	(9, 3)	56	0.645	Forty-six distinct codewords are used.
Code 128	(11, 3, 4)	216	0.705	One hundred two distinct codewords are used.
PDF417[b]	(17, 4, 6)	10480	0.786	Three clusters are used, each containing 929 codewords.

[a] For these binary codes, $r = 2.5$ is assumed.
[b] PDF417 is a two-dimensional code with a regular barcode codeword structure. We will cover two-dimensional codes later in this article.

than mX. The size of the alphabet of an (n, k, m) code is

$$S_{\mathrm{D}}(n, k, m) = \binom{n-1}{2k-1} - 2k \sum_{u=m+1}^{n-2k+1} \binom{n-u-1}{2k-2} \tag{8}$$

And, as can be seen, when

$$m \approx n - 2k$$

the number of distinct codewords reduction is not significant.

The information density calculation used here does not take into consideration the non-information-carrying parts of a barcode, including *the start and stop patterns,* the special codewords or patterns used at the two ends of a barcode, and the *quite zones,* which are the required white space bordering the barcode. In addition, for ease of printing by certain specialized printing equipment, some symbologies do not use the width of the spaces (or bars) to record information. Some others leave a space between adjacent codewords, so this space can be printed with looser tolerance (these symbologies are called *discrete* symbologies). All these variations reduce the information density as calculated above.

Many delta codes can be decoded using the *t-sequence.* This is a feature designed to counter ink-spread, a phenomenon where all bar widths grow (or shrink) in such a way that each bar edge is shifted by the same distance, dx. Given a sequence of element widths (the *x-sequence*) from a scan line,

$$x_1, x_2, x_3, x_4, \ldots$$

the t-sequence is defined as

$$t_1 = x_1 + x_2,\ t_2 = x_2 + x_3,\ t_3 = x_3 + x_4,\ \ldots$$

When ink-spread is introduced, the x-sequence becomes

$$x'_1 = x_1 + 2dx, \qquad x'_2 = x_2 - 2\,dx, \qquad x'_3 = x_3 + 2\,dx,$$
$$x'_4 = x_4 - 2\,dx,\ \ldots$$

where dx is the amount of ink-spread per bar-space edge, but the t-sequence remains unchanged:

$$t'_1 = x_1 + x_2 = t_1, \qquad t'_2 = x_2 + x_3 = t_2, \qquad t'_3 = x_3 + x_4 = t_3, \ \ldots$$

Thus t-sequence decoding is not affected by ink-spread.

Some symbologies are *self-checking.* This is the feature where if one width measurement or one edge location measurement is incorrect, the codeword under consideration becomes invalid. When that happens, a potential *misdecode* (i.e., decoding a barcode into incorrect message) becomes a nondecode, which is considered a more tolerable outcome. Self-checking is realized through selection of codewords such that no two codewords are too similar in their element composition. Such a selection process reduces the number of distinct codewords and the information density from those calculated by Eqs. (3) to (7).

Barcodes may also use checksums to avoid misdecode. Some symbologies dictate how the checksums are used, while others may allow user selection. A common single-character checksum formula is

$$\text{checksum} = \left(\sum_i a_i C_i\right) \bmod S \tag{9}$$

where a_i are nonzero constants, C_i are values the symbology under consideration assigns to the codewords in the barcode, and S is the size of the alphabet of the symbology. The checksum is stored in the barcode, and the calculation is repeated in the scanner. If a codeword is misdecoded, no matter whether it is a user-data codeword or the checksum codeword, calculation with Eq. (9) will not agree with the decoded checksum value, invalidating the decode.

Some symbologies use multiple codebooks to enlarge the allowed alphabet. The idea is similar to using the Latin alphabet but with a method to specify whether the letters should convey words in English, French, or German. With three different interpretations, we effectively obtained an alphabet three times as large. As an example, the size of the Code 128 alphabet is only 102, excluding the start and stop patterns. But by using three codebooks, it has an effective alphabet of all ASCII characters (128 in total) plus all double digits (i.e., 00, 01 to 99). Specially designated codewords are used to switch between codebooks.

BARCODE SCANNERS

Requirements for barcode readers are stringent and diverse. The ideal scanner should be easy and natural to use, fast, accurate, inexpensive, rugged, and durable. In more technical terms, it should read all symbologies one possibly needs and decide automatically which symbology describes a barcode (referred to as *autodiscrimination*), cover a large area, scan barcodes in many angular configurations (rotation, pitch, and yaw) and at very different distances, and read barcodes of low quality (either low print quality or partially damaged). Usually all these are not achieved simultaneously, and the choice of scanners is based on the application's priorities and compromises.

There are at least two ways to categorize barcode scanners, namely, by their scanning mechanism and by the embodiment. By the scanning mechanism, scanners can be divided into laser scanners, where a moving laser spot does the scanning, and imaging scanners, where the scanning is done virtually in electronics. Wand scanners have no scanning mechanism, and the hand motion of a human operator does the scanning. By the embodiment, scanners can be separated into handheld, slot, presentation, wand, and overhead varieties.

In the remaining part of this section we will first discuss the basic steps of barcode signal processing. We will then investigate the signal degrading factors affecting the performance of scanners, which are distortions and noise. We will cover different barcode scanners first according to scanning technology—namely, laser scanning, electronic scanning (imaging scanners), and manual scanning (wands)—and then according to scanner embodiments.

Barcode Signal Processing

A general block diagram of a barcode scanner is shown in Fig. 4. We discuss the parts relating to signal processing in this

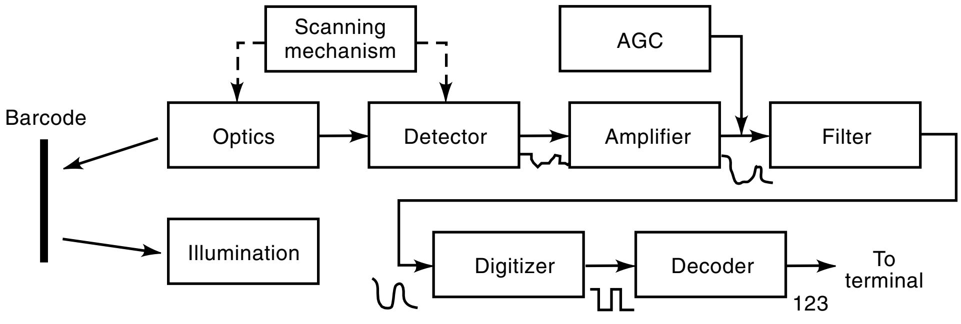

Figure 4. General block diagram of a barcode scanner. Light from the illumination source is scattered by the barcode, and part of the scattered light is focused by the optics onto the detector. Components in the optics may be scanned (in laser scanners), or virtual scan could be performed on the detector (in imaging scanners). Electronic signal conditioning and processing is performed to obtain the text information encoded in the barcode. Not all scanners contain all parts illustrated here, and some parts could be arranged differently.

subsection, while deferring the discussion on the remaining parts.

A barcode scanner scans the field in a scan line, in search of edges between areas of different reflectivity (i.e., bars and spaces). Part of the light scattered by the barcode is collected onto a detector, which converts it into an electronic signal. Specular reflection is avoided when possible to stabilize the signal level.

Signal amplification is often aided by an automatic gain control (AGC) circuit. Electronic filtering is first performed on the signal to block out high-frequency noise. A digitizer finds the bar-space edges represented in the signal. These edges are estimated with either (a) the locations where the signal crosses a particular signal (4), or (b) the zero-crossings of the second derivative of the waveform (5). The intervals between adjacent bar-space edges are measured, which results in the x-sequence.

A decoder translates the x-sequence (or t-sequence) into text message. Autodiscrimination is achieved by finding a symbology that best describes the barcode signal.

Distortion and Noise

The quality of a barcode scanner depends largely on its performance when the input data are not perfect. The imperfections a scanner must contend with include ink-spread, time-scale distortion, convolution distortion, and noise. Distortion and noise are the causes of misdecode. Most symbology-scanner systems can achieve misdecode rates lower than 10^{-6} in normal circumstances.

As mentioned, ink-spread widens all bars wide and narrow by the same amount. The amount of widening depends on the paper and ink used, and therefore it could be different from print to print. Ink-spread is also used in a more general sense to cover all causes of uniform bar width growth (or shrinkage) in the barcode label.

Time-scale distortion occurs when the signal, when mapped onto the scan line, is not sampled at uniform intervals. In wand scanners, this is due to the fact that the velocity of hand motion is not constant. In laser scanners, the reasons may be the nonlinear mapping between the angular scan speed and the linear scan speed, the variation in angular scan speed, the yaw of the barcode, and so on. In imaging scanners, the contributing factors may include the yaw of the barcode and the distortion of the optical system.

Overall, barcode scanners exhibit a low-pass filtering behavior. A low-pass filter in the frequency domain is equivalent to a convolution in the spatial domain, hence the name convolution distortion. The effect is that the *depth of modulation* (DOM) decreases. DOM is defined as the ratio of signal level change caused by adjacent narrow elements versus that caused by adjacent wide elements. At small DOM, estimated edge locations tend to shift from their ideal locations in the x-sequence (6) (Fig. 5).

Both barcode printing and scanning processes introduce noise. Printing noise comes from the print head, the ribbon in a dot-matrix printer, and the paper (e.g., egg cartons). Scanning noise will be discussed later with scanners. Noise causes random error in edge-location measurements and, with a lower probability, introduces false elements.

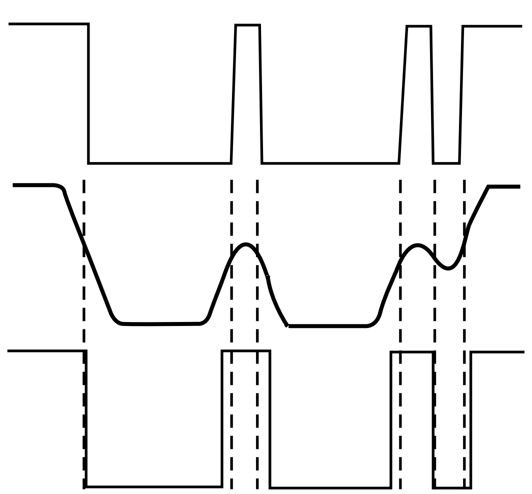

Figure 5. When an ideal barcode waveform (top) is convolved with the kernel of a low-pass filter, in the blurred waveform the depth of modulation decreases, especially for edges between narrow elements (middle). When the rectangular barcode waveform is recreated (bottom), in the form of x-sequence, the estimated edges are shifted from the original locations.

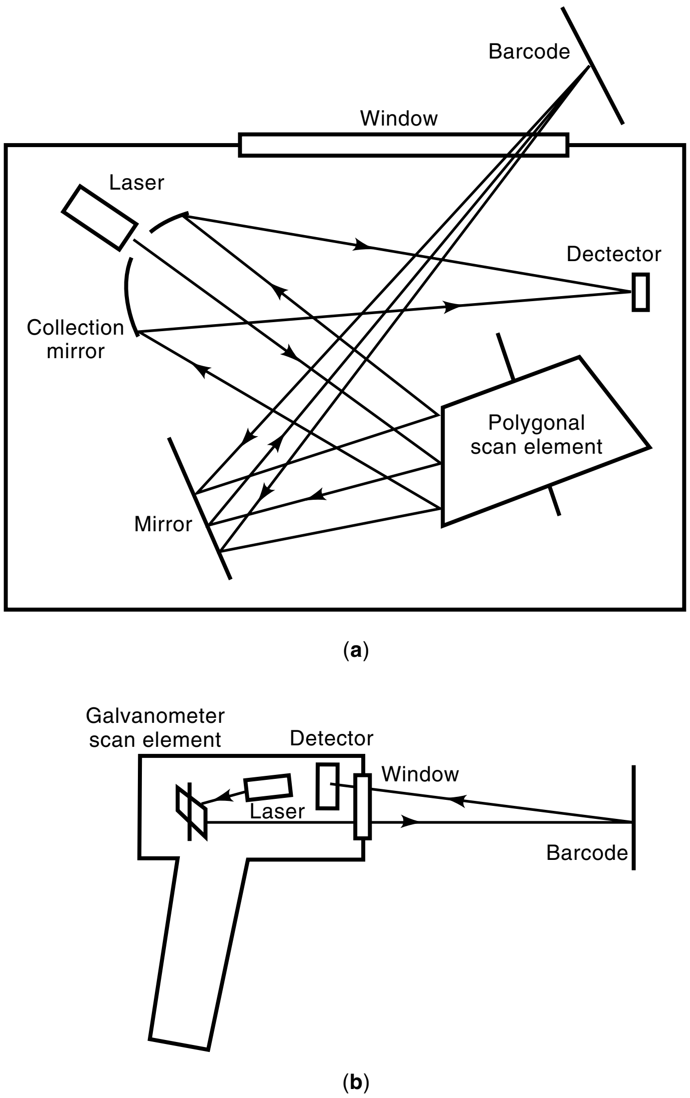

Figure 6. Two configurations of laser scanners: (a) A slot scanner with a polygonal scan element and a retroreflective collection optical system. (b) A hand-held scanner with a galvanometer-type scan element and a staring detector.

Scanning Technologies

In this subsection we will discuss scanners according to the means of scanning employed—that is, laser scanning (laser scanners), electronic scanning (CCD scanners), and hand scanning (wand scanners).

Laser Scanners. As illustrated in Fig. 6, a laser scanner consists of a laser source, a scan element, a window for light to exit and reenter the scanner, and one or more detectors. Some scanners may also have several mirrors in the optical path, as well as a collector element, which is either a lens or a concave mirror. We shall detail some of these parts below.

A laser beam illuminates a small spot that is scanned across the barcode. The two special qualities of a focused laser beam, namely high intensity and low divergence, are both used effectively. The high intensity of the laser illumination differentiates the laser spot from the surrounding area, which is illuminated by ambient light. The low divergence of the laser beam provides laser scanners with large working range. First-generation laser scanners used He–Ne lasers, while most current laser scanners use red laser diodes emitting at 650 nm to 675 nm.

The working range achievable by a laser scanner depends primarily on signal strength and the DOM. Depending on the X dimension of the barcode, the working range achievable by a laser scanner can be tens of cm to multiple meters. Barcodes with large X dimensions may be scanned from a large distance, and the limiting factor is likely the signal strength (the maximum laser power emitted from scanners is regulated by government agencies). Barcodes with smaller X dimensions are more likely limited by DOM.

The DOM is determined partly by the laser beam size and the electronic filtering applied to the received signal. Often the laser beam from a scanner is Gaussian, or close to it. The transverse amplitude field distribution of a TEM_{00} Gaussian beam is given by (7)

$$E(x, y, z) = A(z)\exp\left[-\frac{x^2+y^2}{\omega^2(z)} - j\Phi(x^2+y^2, z)\right] \tag{10}$$

where z is along the beam propagation direction, A is a real-valued amplitude, and Φ is a real-valued phase factor. The beam size (here we refer to the beam radius, instead of diameter, to simplify the notation), $\omega(z)$, is given by

$$\omega(z) = \omega_0\left[1+\left(\frac{z-z_0}{z_R}\right)^2\right]^{1/2} \tag{11}$$

where ω_0 is the beam waist size (minimum value of ω), z_0 is the beam waist location, and z_R is the confocal parameter, related to ω_0 by

$$z_R = \frac{\pi\omega_0^2}{\lambda} \tag{12}$$

where λ is the laser wavelength. Usually the beam waist is optimized according to the X dimension of the intended barcode so that maximum working range can be achieved. For example, to get the maximum range in which

$$\omega(z) \le aX$$

where a is a constant related to the design of the scanner, the beam waist size should be set to

$$\omega_0 = \frac{aX}{\sqrt{2}} \tag{13}$$

Different optimization merit functions may be used to include linear scan-speed and electronic filtering, as well as other factors, and the optimization solution is likely not analytical.

An effective beam size can be defined to include both the Gaussian beam size and the effect of low-pass electronic filtering (4). The system impulse response can be expressed as a convolution:

$$h_s(t) = h(t)^*s(t) \tag{14}$$

where h is the impulse response of the electronic filter, and s is the linear impulse response of the laser beam:

$$s(t) = \frac{\int E^2(vt, y, z)\,dy}{\iint E^2(x, y, z)\,dx\,dy} \tag{15}$$

where v is the linear velocity of the laser spot, and x is the direction of the scan (parallel to v).

The transfer function of a typical electronic filter, which is the Fourier transform of h, may be expressed as

$$H(f) = \prod_k \frac{1}{1 + i2\pi\tau_k f} \tag{16}$$

for the low-pass filter used in the electronics. The effective beam size can then be approximated as

$$\omega_s(z) = \sqrt{\omega^2(z) + 4\sum_k \tau_k^2} \tag{17}$$

Laser scanners are frequently supersampled; that is, the spacing between samples is smaller than the laser spot size. Supersampling helps to achieve an actual resolution that is smaller than the laser beam size (the related topic of supersampling imager pixel arrays is discussed in Ref. 8). Because of the availability of supersampled data, laser scanners often perform all signal processing in the analog domain before digitizing the data into x-sequences.

Often a laser scanner uses either a polygon or a galvanometer to deflect the laser beam and produce the scan line (scanners that use moving holograms to generate the scan line will be discussed with slot scanners). The scanning is usually not at constant speed, causing systematic time-scale distortion. When the scanning surface or the laser beam is not perpendicular to the rotational axis, the output beam often does not stay in a plane, producing a scan bow (9,10).

The scattered light from the barcode is collected by either one or more staring detectors [Fig. 6(b)] or, more likely, a retroreflective system (described below). An example is shown in Fig. 6(a). Staring collection systems are simple, but they receive all ambient light in the field-of-view, which increases noise (see discussion below). A retroreflective collection system shares the scanning element between producing the output beam and collecting scattered light, and therefore it can use a small collection field-of-view that follows the scanning beam. The reduced field-of-view provides an increased signal-to-noise ratio.

Many retroreflective laser scanners allow the blurred image of the laser spot to overfill the detector when the object distance is a short, which is referred to as optical AGC (11). An optical AGC is sometimes preferred over an electronic AGC because of its instantaneous response. Following Fig. 7, we can see that

$$r = \left(1 - \frac{s}{f} + \frac{s}{L}\right)R \tag{18}$$

where f is the focal length of the collection lens, and all other parameters are defined in Fig. 7. An ideal optical AGC is achieved when $s = f$, or the detector is at the back focal plane of the collection lens. If the detector is a circular one with radius r_0, then the received power (to the approximation that

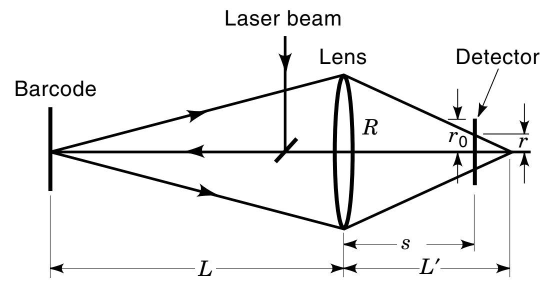

Figure 7. The equivalent retroreflective collection optical system of a laser scanner. Optical AGC is realized through the choice of detector location s and the detector size r_0.

the solid angle subtended by the collection lens is the same as the projected solid angle) is given by

$$P_o = \begin{cases} P_i\left(\dfrac{r_0}{s}\right)^2, & L < \dfrac{sR}{r_0} \\ P_i\left(\dfrac{R}{L}\right)^2, & L \geq \dfrac{sR}{r_0} \end{cases} \tag{19}$$

where P_i is the laser beam's optical power. This calculation also assumes that the laser beam produces an ideal nondivergent spot throughout the working range. Other issues deviating from the ideal optical AGC include (1) the collection lens not being focused at infinity and (2) shape mismatch between the detector and the aperture.

Ambient light adds noise to a laser scanner, because shot noise is proportional to the total light intensity at the detector (7, Chapters 10 and 11):

$$S_{\text{shot}}(f) = 2q\bar{I} \tag{20}$$

where $\bar{I}$ is the direct-current (dc) component of the photocurrent, and q is the charge of an electron. For a laser scanner to be able to operate under ambient light as bright as sunlight, a narrow-band optical filter matching the laser wavelength is usually used. Artificial light sources, even though not comparable in intensity to sunlight, also cause concern because they may be modulated at a frequency that interferes with the barcode reading. Laser speckle noise is another unique noise for this type of scanner. The noise power spectral density is given by (12)

$$S_{\text{speckle}}(f) = \frac{(\lambda z\langle i\rangle)^2}{\sqrt{\pi}v\omega(z)A_d}\exp\left[-\left(\frac{\pi\omega(z)f}{v}\right)^2\right] \tag{21}$$

where $\langle i\rangle$ is the ensemble average instantaneous photocurrent, z is measured from the receiver (either a collection lens or a bare staring photodetector), v is the spot velocity, and A_d the size of the receiver. As shown in Eq. (21), the speckle noise is proportional to the photocurrent and hence the laser power (often referred to as a multiplicative noise), and the signal-to-noise ratio cannot be improved by increasing the laser power.

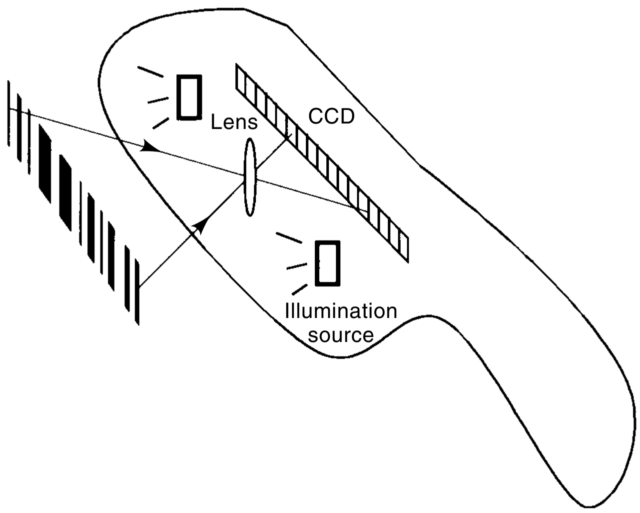

Figure 8. Illustration of the important components in an imaging scanner, including a linear CCD, a lens, and two illumination sources.

CCD Scanners. The major components of an imaging scanner are illustrated in Fig. 8 and are discussed in the following. Imaging scanners for one-dimensional (1-D) barcodes usually use linear CCD arrays (13) as the virtual scanning device. The CCD may have a few thousand pixels, and the barcode is imaged on the CCD by a single lens or by a lenslet array. For CCD scanners, the number of pixels in the imager array and the field-of-view determine the available resolution (the minimum resolvable feature size). A/D conversion is commonly performed on the waveform to preserve the resolution.

The working range of an imaging scanner is predicted by (14)

$$WR = \frac{2X\rho L}{R} \tag{22}$$

where X and R are as defined before, L is the object distance, and ρ is a constant related to the required minimum DOM. A requirement of 20% DOM leads to $\rho \approx 0.83$. The working range of a CCD scanner, given by Eq. (22), is limited compared to that achievable by a laser scanner. Equation (22) is based purely on geometrical optics, but some CCD scanners use very small apertures which require diffraction-related analysis.

For CCD scanners, ambient light contributes to barcode illumination. With insufficient ambient light, the scanner may need to lengthen the exposure time or turn on its own illumination. Longer exposure time subjects the scanner to motion-induced blur, as usually either the scanner or the object bearing the barcode is in motion.

The transfer function and noise of CCD scanners are common to those of CCD imagers (13) and are not discussed here.

Wand Scanners. Wand scanners are the simplest and least expensive scanners, with the lowest scanning performance. They do not contain any scanning mechanism—the human operator does the scanning. A strict wand scanner usually transmits the scanned signal to a separate box for decoding. Newer types of hand-scanned scanners (e.g., credit-card-shaped) may incorporate the decoding electronics in the same hand-held physical unit.

Wand scanners work in contact or very close proximity with the barcode. They use an incoherent light source for illumination. The light collection optical train shares the same optical opening on the unit with the illumination optics. The self-clocking characteristic of symbologies is most important for wand scanners, as the hand-scanned scan line has a velocity that varies significantly over a barcode.

Without mechanical or electrical scanning, wand scanners do not get as much repeated data as laser or imaging scanners, and its decode speed (expressed in decodes per second) suffers as a consequence. The contact requirement may also damage the barcode, making this type of scanner less suited for environments where the barcode is reused multiple times.

Scanner Embodiments

In this subsection we discuss several common scanner embodiments. These include hand-held scanners, slot scanners, presentation scanners, and overhead scanners. We also present scan engines, which are miniature barcode scan modules that can be integrated into other devices. Wand scanners, also a unique scanner embodiment, have been discussed above.

Hand-Held Scanners. Nonwand hand-held scanners include mechanical or electronic scanning mechanisms. Most applications where the distance between the scanner and the barcode is highly variable use laser-based scanners. In applications where the scanner can be in contact with the barcode, CCD-based hand-held scanners can be used. A hand-held scanner can scan multiple times while the scanner's trigger is pulled, and this repetition helps to boost the scanner's decode speed.

Hand-held laser scanners use a mechanical scanning mechanism, which is usually a galvanometer driven by a miniature motor. The motor drives either a small mirror or the laser itself. The former is generally preferred because that the output beam is scanned at twice the angular velocity as the mirror. The laser scan line also serves as a visual feedback to the operator, indicating which barcode is scanned, how the scan line is aligned with the barcode, how long the scan line is, and so on. Sometimes an elliptical beam profile is used to average over possible noise in the barcode (Fig. 9).

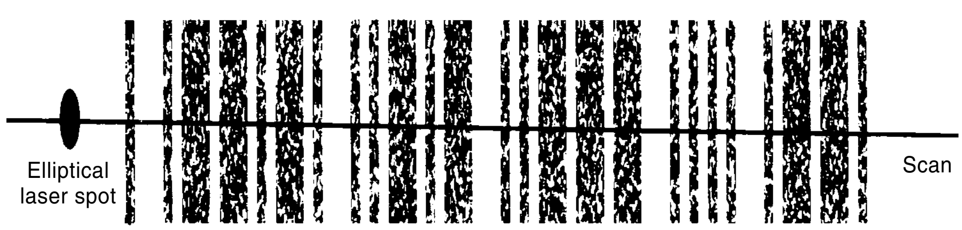

Figure 9. An elliptical beam averages over noise in the barcode. Noise in barcodes is probably caused by the printer (print-head defect, ink shortage, worn-out ribbon, etc.) or the media (paper quality, watermark, lamination, shrink-wrapping, etc.).

Some of hand-held imaging scanners have working ranges of tens of centimeters, while others only work when the barcode is nearly in contact with the scanner.

Slot Scanners. Slot scanners are most often used in supermarkets. The name is derived from the design of first-generation devices, which had a pair of crossed slots where laser beams come out to scan the merchandise from the bottom. Required to perform with high scan speed (see below), all slot scanners are laser scanners. Most slot scanners use an asymmetrical polygon, in which all surfaces have different slope angles in relation to the rotational axis, to move the laser beam. Some slot scanners use a holographic plate to move the laser beam, which we will discuss later.

The most important performance factor in a slot scanner is its "scan speed," a composite measure that includes human factors. The achievable scan speed relates to the size of the "scan zone" and the number of sides the scanner covers. To translate these terms into technical language, one can imagine a package being moved over the scanner (which can be modeled as linear motion at constant speed). The scan zone is the region where a barcode on the package is scanned. Ideally the scan zone should be wide enough to cover the entire belt, but should be more compact in the direction along the belt. To the scanner manufacturer, the problem is that barcodes facing different directions may be scanned at different locations along the belt. If these different locations are too far from each other along the belt direction, it may be difficult for the operator to distinguish whether the item scanned is the intended one or one still on the belt. The number of sides a scanner covers is another ergonomics-related issue. If a scanner can cover more sides of a package, the cashier needs to align the package less frequently. Most slot scanners can cover at least the leading and bottom sides, while some newer ones can cover the far and trailing sides, and even partially cover the near and top sides.

The fact that a slot scanner looks at an object from different sides means that it also has an extremely large overall field-of-view. All slot scanners, therefore, use the retroreflective collection system. Because of vignetting, the effective collection area, and hence the signal power, can change significantly along the scan line. This puts special requirements to the electronics, especially the AGC.

Laser spot ellipticity due to the angle between the laser beam and the barcode causes an additional problem for slot scanners. As shown in Fig. 10, the elliptical spot can partly act as an averaging filter, similar to that shown in Fig. 9, in a horizontal scan line. But in a vertical scan line, the elongated spot acts as an additional low-pass filter, which has the adverse effect of reducing the DOM.

Holographic scanners open new opportunities to optical design (15). This is because the beam-angle variations do not have to come at the cost of particular internal beam paths, and different scan lines can have different focusing powers. The former is helpful in producing more varied scan lines to cover different sides of the object, while the latter is useful in producing larger-than-usual scan zones. Furthermore, the collection lens can be built on the same rotating plate that generates the scan lines. This allows for more flexible optical AGC. For example, the value of R in Eq. (18) can now be tailored for scan lines with different L.

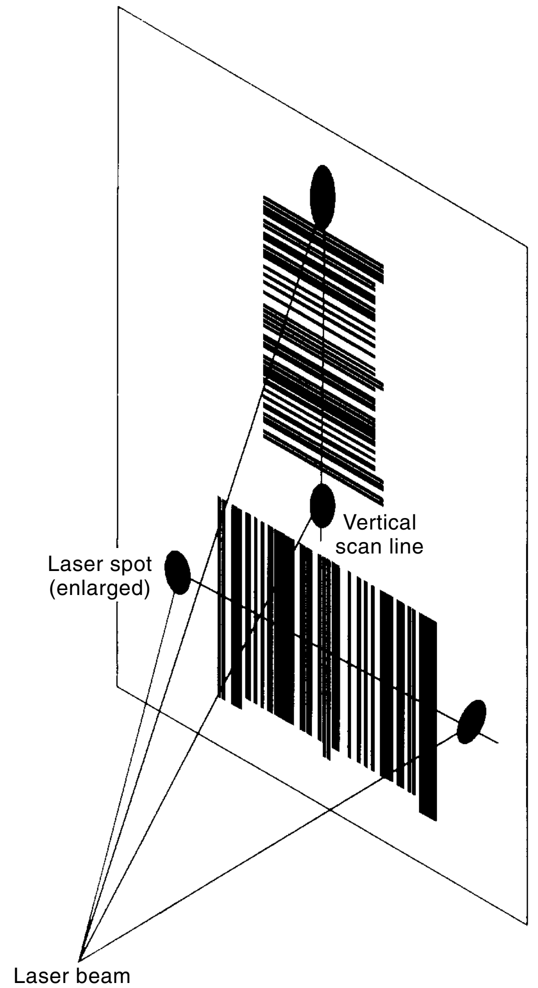

Figure 10. In a slot scanner, the ellipticity of the laser spot is caused by the angle between the laser beam and the barcode plane. This is not very critical in a horizontal scan line, but is a serious concern in a vertical scan line.

Presentation Scanners. These are mostly used in department stores, drug stores, libraries, and so on, in applications where it is preferable that the scanner not be maneuvered by the human operator and where the checkout space is limited. The barcode to be decoded is *presented* (hence the name) to the scanner and left in its field-of-view until decoded.

For presentation scanners, working range is less important. Laser scanners allow more samples on one scan line and thus can have a larger field-of-view than imagers at the same resolution, and therefore they are a common choice. Frequently an alignment requirement on the barcode is not desired, even though the barcode is not over-square. A star-shaped pattern of scan lines, discussed earlier in this article, is commonly used. Furthermore, to alleviate requirements on translational alignment, each scan line in the star pattern is duplicated into a group of parallel scan lines.

Overhead Scanners. High-speed overhead scanners are used to scan barcode-bearing packages traveling on conveyer belts. The width of the belt can be up to 1 m, while the speed of the belt can be up to 200 m/min. These requirements put high data rate demand on the scanner.

Laser-based overhead scanners usually employ multiple scan lines, and omnidirectional scanning is helped by printing the barcode in two orthogonal directions [see Fig. 3(b)]. With two identical barcodes, the number of scan lines of the scanner is effectively doubled. For example, if three scan lines are used, we can use $N = 6$ in Eq. (2), and the relationship between the width and height of the barcode becomes

$$\frac{W}{H} \leq \frac{1}{\tan(\pi/12)} \tag{23}$$

This allows the width of the barcode to be almost four times the height. In reality, more scan lines are needed to account for the objects' motion. Nevertheless, this method of achieving omnidirectionality is preferable because a scan line that is nearly parallel to the conveyer-belt motion direction cannot effectively cover the width of the belt and therefore has to be duplicated. Holographic scanners are used in some applications—for example, to increase the working range.

Imager-based overhead scanners use high-speed parallel processing, which allows omnidirectional decoding of barcodes and even 2-D codes. As we will discuss shortly, the high-speed reading of 2-D codes requires imager-based scanners.

Sometimes a package on the belt may not carry the barcode on the top, but on a different side. If other sides of the package are also to be scanned, the speed and angular requirement for the scanner becomes much more stringent. Usually several scanners are used to form such a high-throughput system.

Scan Engines. Scan engines are miniature barcode scan modules, which are mostly laser-based. Because of the ease of integration they provide, they are widely used in hand-held mobile computers and checkout terminals. Some hand-held scanners also employ scan engines inside.

With a volume of only several cubic centimeters, a scan engine adds the fast and accurate data input method of barcode scanning to a normal computer. Some scan engines contain integrated decoders as well, and the communication between the scan engines and the host computer is through a standard serial communication port. Other scan engines do not contain an integrated decoder; thus the system is simpler and more economical, and the host computer performs the decoding.

TWO-DIMENSIONAL CODES

Two-dimensional codes are generally used as portable data files, where the complete data file related to an item is recorded in the code. This contrasts with the short string of text recorded in a barcode which serves as an index value to a database. By using 2-D codes, the reliance on the network and database server is eliminated. To record more than tens of characters in a barcode is not practical, so 2-D codes are invented to record more data in less area, which facilitates printing and scanning.

In 2-D codes, data are recorded in both directions. Although the most direct way to use both directions to record data is to use square packing, other packing methods have also been used. Particularly, a class of 2-D codes called *stacked barcodes* are built with stacks of 1-D codewords, and their modules are usually taller than wide. Calculating information density for 2-D codes is more involved than that for 1-D barcodes, because different 2-D codes have very different amount of overhead, which includes finder patterns, support structures, codeword overhead, and error-correction overhead (discussed later). To the first order of approximation the reading performance (such as working range) does not depend on the linear size, but depends instead on the area of the smallest module (16).

Dozens of 2-D symbologies have been invented (see Table 2 for a partial listing), but only a few of them are standardized and widely adopted. In this section we introduce three of these that have published standardized specifications and have been adopted by some industries as the standard symbology: PDF417, MaxiCode, and DataMatrix [Fig. 11(a–c)]. In addition, we also cover postal codes [Fig. 11(d) and 11(e)]. Because postal services around the world are all government-owned monopolies, postal codes are published and maintained by individual postal services, who also regulate their use.

PDF417

PDF417 is the most widely adopted 2-D code, and it can store over one kilobyte of user information in one barcode. True to its stacked barcode nature, PDF417 symbology exploits many ideas developed in 1-D barcodes, often to a greater extent. The PDF417 name refers to a portable data file with a (17, 4) 1-D codeword structure. These 1-D codewords are arranged in rows, each row having *row indicator* codewords at the left and right, next to the start and stop patterns. As can be seen from Fig. 11(a), the start and stop patterns of PDF417 are continuous throughout the height of the barcode.

PDF417 uses three codebooks (called *clusters* in PDF417), each containing an exclusive set of codewords to encode the same data (this contrasts with the practice of using the same codewords to encode different data in some 1-D barcode sym-

Table 2. A Partial Listing of 2-D Codes, Excluding Postal Codes

Name	Standardized	Public Domain
2-DI	No	No
Array Tag	No	No
Aztec Code	Yes	Yes
Codablock	Yes	Yes
Code 16K	Yes	Yes
Code One	Yes	Yes
CP Code	No	No
DataGlyph	No	No
Dot Code	No	No
HueCode	No	No
LEB Code	No	No
MaxiCode	Yes	Yes
MicroPDF417	Yes	Yes
MMC	No	No
PDF417	Yes	Yes
QR Code	Yes	Yes
SmartCode	No	No
Snowflake Code	No	No
SoftStrip	No	No
Supercode	No	Yes
Vericode	No	No

Code in public domain can be used without fee.

(a)

(b)

(c)

(d)

(e)

Figure 11. Several two-dimensional codes, including (a) a PDF417 symbol, encoding 151 numeric and mixed-case alphabetical characters, (b) a MaxiCode symbol, encoding 93 numeric and uppercase alphabetical characters, (c) a DataMatrix symbol, encoding 10 mixed-case letters, (d) a PostNet code (US postal code), and (e) a Japanese postal bar code.

bologies). The cluster number of a particular codeword is defined as:

$$c = (x_1 - x_3 + x_5 - x_7) \bmod 9 \tag{24}$$

where x_i is the width of ith element of the codeword. Only codewords in clusters 0, 3, and 6 are used in PDF417, making the codewords self-checking.

Codewords in each row of a PDF417 barcode have the same cluster number. Counting from the top of a PDF417 barcode, the cluster number of a codeword in the ith row is

$$c = (3i - 3) \bmod 9 \tag{25}$$

This feature provides vertical tracking information for a tilted scan line. For example, if after a series of cluster 0 codewords a cluster 3 codeword is observed, the decoder may conclude that the scan line is tilting downward.

2-D codes contain more data than their 1-D counterpart, and therefore they require more robust data protection than simple checksums. The error-control method that PDF417 utilizes is the Reed–Solomon Code (hereafter RS Code, see CHANNEL CODING), which allows not only error detection, but also error correction of multiple codewords. PDF417 permits user-selectable error-correction levels. Usually an error-correction capability of about 20% is used, but more (or less) can be selected if the application is more (or less) demanding.

The error-correction capability is manifested in the number of added error-control codewords added (readers familiar with or interested in error-control theory should note that the use of codeword here does not agree with its usage in error-control theory). These error-control codewords are generated with equations that parallel Eq. (9), but in a manner such that all the user-data related and error-control codewords are mutually interconnected. Error-correction codes such as RS Code can correct errors, where a codeword is misdecoded from the barcode, or erasures, where the codeword in the barcode is not decoded, or a combination of both, up to the maximum level of error-correction capability. As for the checksum calculation, it does not matter whether the error or erasure occurs at a data codeword or an error-control codeword. The maximum error correction capability of an RS Code with κ error-control codewords is

$$\epsilon + 2h \le \kappa \tag{26}$$

where ϵ is the number of erasures, and h is the number of errors. A detailed description of RS Code can be found in ALGEBRAIC CODING THEORY.

The concept of error-detection budget is also introduced to PDF417 to further reduce its misdecode probability (17). This budget, b, is a number of error-control codewords reserved from being used for error correction, so that Eq. (26) is revised as

$$\epsilon + 2h \le \kappa - b \tag{27}$$

This reduction reduces significantly the misdecode probability, at the cost of slightly reducing the error-correction capability (18).

High-level encode/decode is an additional layer of translation in PDF417. This concept is a direct extension to the codebook concept as practiced in some 1-D barcodes. With this concept, the PDF417 codewords, each recording a value between 0 and 928, does not record the user data directly. Instead, translation is done to facilitate data compression/compaction. Nowadays a common practice in 2-D codes, the data compression/compaction method used in these codes is different from those employed in general data-compression schemes. General data compression are most effective when the data model is adapted to the data. 2-D codes use prior knowledge of the likely data types [e.g., numeric, alphanumeric, electronic data interchange character sets (19), etc.] to encode with preselected schemes. The benefit is reduced overhead and more efficiency, especially suited for the typical amount of data encoded, which is much smaller than that treated by general data compression schemes.

MaxiCode

MaxiCode has been adopted as a standard 2-D code for high-speed sortation by several standard bodies. A MaxiCode symbol contains a hexagonal matrix of hexagonal elements surrounding the finder pattern [Fig. 11(b)], and it can encode up to 84 characters from a 6-bit alphabet.

Designed for high-speed over-the-belt scanning application, MaxiCode has an isotropic finder pattern and a fixed size. Commonly referred to as the “bull’s eye,” the finder pattern follows the ring code tradition. Both isotropic finder pattern and fixed size facilitate high-speed image processing by hardware.

As PDF417, MaxiCode also uses RS Code and high-level encoding/decoding. Two error-correction levels are available for user selection.

DataMatrix

DataMatrix [Fig. 11(c)] has been adopted as a standard 2-D code for small item marking. Applications include the marking of integrated circuit and parts. A typical symbol encodes less than 100 bytes of user data, although the specification allows much more.

A DataMatrix barcode consists of square modules arranged in a square grid pattern. The X dimension and number of modules are variable. The outer enclosure is the finder pattern, which contains two solid sides and two dotted sides. From an error-correction point of view, two major varieties of DataMatrix exist: One uses a convolutional error-correction code, whereas the other uses an RS Code.

Postal Codes

Postal codes [Fig. 11(d) and 11(e)] are a special kind of 2-D code because only the vertical dimension encodes data, while the horizontal direction is used only to produce a periodical signal which helps to maintain reading synchronization. The pioneer of postal codes, the United States Postal Service PostNet, uses two types of bar heights and is referred to as 2-state codes. Many other postal services in the world, such as those in Australia, Canada, Japan,and the United Kingdom, have designed 4-state codes where each bar can record up to 2 bits of information. The amount of data stored in postal codes is similar to or slightly more than that possible in 1-D barcodes.

TWO-DIMENSIONAL CODE SCANNERS

As mentioned earlier, PDF417 belongs to stacked barcodes, which can be scanned by a special class of scanners. On the other hand, reading most other 2-D barcodes requires 2-D imaging scanners.

PDF417/1-D Barcode Scanners

Stacked barcodes can be scanned by scanners that produce parallel scan lines. For an application requiring frequent PDF417 barcode scanning, or high scanning throughput, scanners which generate raster patterns can be employed. The scan pattern of these laser scanners mimics the raster pattern of television sets. These scanners also autodiscriminate between PDF417 and 1-D barcodes. Some of these can even scan postal codes. In addition, there are imager-based PDF417/1-D barcode scanners specifically designed to read barcode-bearing cards (such as driver’s licenses).

Some PDF417/1-D scanners produce only 1-D scan lines. Either laser- or imager-based, these 1-D scanners are the most economical PDF417 scanners, and they can autodiscriminate among PDF417 and 1-D symbologies. The drawback is that the time needed to scan a PDF417 barcode is relatively long. The operator has to swipe the scan line up and down the barcode, while the scan line itself is swept from left to right (and back from right to left for laser scanners) automatically by the scanner.

General Two-Dimensional Code Scanners

Imager-based scanners are required for general scanning applications involving 2-D and 1-D barcodes. Hand-held 2-D barcode scanners usually employ 2-D CCDs.

If the 2-D/1-D barcodes are carried by sheet paper, then regular flatbed scanners can be used to image the paper, and the computer connected to the scanner can perform the decode. For high-speed over-the-belt applications, such as using MaxiCode for sortation, linear CCD-based scanners are used (as discussed earlier). DataMatrix codes are often so small that machine-vision equipment is required to scan them. But because of the special barcode features designed in these codes, especially the error-correction code employed, the read-rate and the accuracy achievable are still much higher than reading regular text with the same machine-vision equipment.

CONCLUDING REMARKS

We live in the age of information. Barcodes and 2-D codes, together with radio-frequency identification (RF-ID), magnetic-strip cards, smart cards, and contact memory devices, have become some of the preferred ways to input information quickly and accurately into computers and computer networks. With easy, quick, and accurate access to information, the computers and networks can then better help us to complete our work better and more efficiently. And we are still far from realizing the full potential that these technologies can bring.

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JACKSON DUANFENG HE
Symbol Technologies, Inc.

MASSES. See MASS SPECTROMETERS.

MASS MEASUREMENT. See WEIGHING.