
Elements of a Bar Code System

Application Note 1013

Introduction

Bar code technology provides an accurate, easy, and inexpensive method of data storage and data entry for computerized information management systems. A properly designed bar code system can offer substantial improvements in productivity, traceability, and materials management, thereby yielding significant cost savings.

A thorough understanding of the elements of a bar code system is essential in the design and implementation of the system. This application note examines the six major elements of a bar code system: symbology, media, printer, operator, scanner, and decoder. The principle criteria for selecting a code and the supporting equipment is presented along with a discussion of the interaction of the system elements. An analytical technique for evaluating system errors and determining the decodability of a bar code symbol is also presented.

Fundamental System Design

There are four main areas to consider in the design of a data storage and retrieval system.

1. What data will be stored and retrieved?
2. How will the data be stored?
3. How will the data be retrieved?
4. How will system performance be measured?

This section of the application note will provide answers to these questions for a bar code data storage and retrieval system. A detailed discussion of the individual system elements will be provided in later sections of the note.

What Data Will be Stored and Retrieved?

The user's application and the data requirements of the information management system will determine the type of data stored in bar code format and, subsequently, retrieved for entry into the computer. The most common type of data stored in bar code is item identification information used for inventory control, work-in-process tracking, distribution tracking, and other material management functions. In these applications, the bar code symbol may represent a product number, serial number, or an alphanumeric description of the item.

Bar codes are also being used in

an increasing number of applications where information about an item or a transaction must be accurately entered into the host computer. The data represented by the bar code symbol in a sampling of these applications is listed below:

- **Item location** for items in raw stores, work-in-process, finished goods, or a distribution facility.
- **Employee identification** for time and attendance recording, productivity measurement, equipment check-out, or task accountability.
- **Assembly steps or process steps** for monitoring the status of items in manufacturing or repair environments.
- **Equipment settings** for configuring test equipment.
- **Inspection results** for items subjected to quality assurance inspections.
- **Failure mode** for items which fail during reliability testing or in the field.

How is the Data Stored?

Bar code data is stored as a series of bars and spaces which are printed on a media. The bar/space pattern required to represent an individual character will depend on the bar code symbology used.

When selecting a symbology, the data format (numeric or alphanumeric), the number of characters in the message, the space available for the symbol, and existing industry standards should be considered.

The media and printer together provide the means for symbol generation. The media used is typically a label, card, or document. Symbol printing may take place either real-time, on-demand or off-line in a batch, pre-printing process. There are several things which must be considered when selecting the bar code media and printer:

1. The data source. The system that generates the raw data to be stored must be able to interface to a printer that can create the desired bar code label.

2. The media characteristics. The media selected to support the bar code symbol must be durable enough to withstand the expected wear. It must also have optical properties which are consistent with the requirements of the scanning equipment used.

3. The printing technique. The printing technique, the print element size, the printer tolerances, and the optical properties of the ink will together determine whether readable bar code symbols of the desired resolution can be generated.

4. The system information flow. The availability of information which determines the bar code message to be printed will influence whether a real-time, on-demand printer is required.

How is Data Retrieved?

Data is extracted from a bar code symbol with an optical scanner that develops a logic signal corresponding to the difference in

reflectivity of the printed bars and the underlying media (spaces). The serial data stored in the symbol is retrieved by scanning over the printed bars and spaces with a smooth, continuous motion. This motion can be provided by an operator moving a hand-held wand, by a rotating mirror moving a collimated beam of light, or by an operator or conveyor system moving the symbol past a fixed beam of light.

The logic signal supplied by the scanner is translated from a serial pulse stream into computer readable data by a decoder. The bar code reader which houses the decoder must interpret legible bar code symbols accurately, provide feedback to the operator, and transmit the data to the computer. The decoding software should be designed to be tolerant of errors introduced by the printer, wand, and operator without sacrificing accuracy. A high tolerance of errors will enable the decoder to read a wider range of printed symbols and will result in a more friendly interface to the operator.

The scanner and decoder are commonly configured as a subsystem for bar code data entry. The location of the symbol, the frequency of scans, and the point of data entry will determine whether a hand-held or stationary scanner is needed. If a hand-held scanner is needed, then these parameters, together with the data management and operator feedback requirements of the system, will determine whether on-line or portable equipment is appropriate for the application.

When a hand-held wand is used, the operator becomes an important part of the retrieval system.

The speed, acceleration, and orientation of the wand as it is moved across the bar code symbol will influence system performance.

How Will System Performance be Evaluated?

The performance of a bar code system is generally described in terms of two parameters. The first parameter is called first read rate. This term is defined as the ratio of the number of good scans or reads to the number of scan attempts. A good bar code system should offer a first read rate of better than 80% in the actual use environment when well printed symbols are scanned. A low first read rate is normally caused by a poorly printed symbol or by improper operation of the system. It may, however, also result if the resolution of the scanner is not well suited to the resolution of the symbol or if the decoding algorithm is not very tolerant of system errors.

The second parameter used to evaluate system performance is substitution error rate. This is the ratio of the number of invalid, or incorrect characters entered into the data base to the number of valid characters entered. Substitution error rate is dependent on the structure of the bar code symbology, the quality of the printed symbol, and the design of the decoding algorithm. One code which has received a great deal of substitution error testing is the 3 of 9 code. A well designed decoder for this code should offer a substitution error rate well below one error out of a million characters.

In addition to these two parameters, it is important to evaluate the downtime which may be experienced by the system and the

effect of downtime on productivity and/or data base accuracy. The durability, reliability, and serviceability of the equipment should be considered in this evaluation.

The next section of this application note provides information needed to evaluate and select the bar code symbology. A detailed description of six popular industrial bar codes is also included. The remaining sections will provide information regarding the media, printer, operator, scanner, and decoder.

Bar Code Symbology

The process to convert a computer message into a bar code symbol is a simple, four-step process. (Refer to Figure 1.) The sequence begins with establishing the type of data to be represented and the number of characters in the message.

The second step is the translation of this human-readable information into a binary sequence. The number and value of the binary bits are determined by the bar code symbology selected. Figure 1 shows the human readable character "72" being translated into the binary sequence prescribed by the 2 of 5 bar code family.

The third step is the creation of the bar/space pattern that represents the binary word defined in step 2. The Industrial 2 of 5 code has been used in Figure 1. Note that a narrow bar represents a logic zero, and a wide bar represents a logic one.

The last step is to format the individual bar code characters into a symbol that represents the complete message. Figure 2 shows the elements of the bar code symbol. The complete symbol consists of

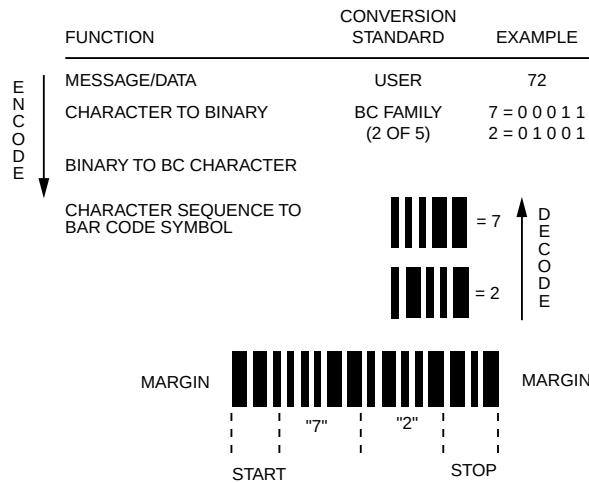


Figure 1. Symbol Encode-Decode Sequence.

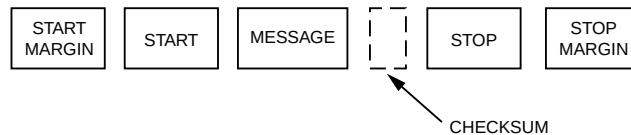


Figure 2. Bar Code Symbol Structure.

start and stop margins, start and stop character patterns, the data or message characters, and an optional checksum character.

The start and stop margins, or quiet zones, are void of any printed characters or bar information and are typically white. The margin areas are normally used to instruct the bar code decoder that the scanner is about to encounter a bar code symbol.

The start character, which precedes the first character of the bar code message, is a special bar/space pattern used to identify the beginning of a bar code symbol. The decoder must recognize the presence of this character before continuing to process the serial pulse stream from the scanner. This adds to the security of the symbology by ensuring that a bar code symbol is being scanned, not some other sequence of reflective

and non-reflective areas which may, coincidentally, have the same pattern as one of the characters in the symbology.

The stop character is also a special bar/space pattern, but its purpose is to signal the end of the symbol. The decoder must recognize the stop character to know that the complete symbol has been scanned and that it may, if the characters are valid, both transmit the message and provide "good read" feedback to the operator. The use of a stop character will, therefore, improve data base accuracy by ensuring that incomplete messages are not entered into the data base. When a checksum character is used, the stop character also instructs the decoder to perform the checksum calculation on the last character of the message.

The bar/space patterns used to

encode the start and stop characters generally do not have a symmetrical binary sequence. This asymmetry allows the start and stop characters to be used interchangeably because the decoder is able to differentiate between scanning in the forward and reverse directions. When the symbol is scanned in the reverse direction, the decoder will reorient the message characters to their correct order prior to checksum calculation or message transmission. Consequently, bi-directional scanning is possible when start and stop characters are used.

A required, or optional, checksum character is defined by most bar code symbologies. The identity of the checksum character is determined when the symbol is created by an arithmetic operation performed on the characters in the message. When the symbol is decoded, this same arithmetic operation is performed and the resulting value is checked against the value of the checksum character in the symbol. The message is entered into the data base only if the check sum character is valid. This procedure greatly reduces the probability of a message character other than the one originally encoded entering the data base, thus improving data base accuracy. When used, the checksum character becomes the last character in the symbol, immediately preceding the stop character.

The general structure of a bar code symbol is implemented differently in each of the numerous bar codes which have been developed. The various symbologies available can be categorized according to the encoding technique used, the character set available—numeric or alphanumeric, and the information density at a specific

Table 1. Common Bar Code Types

Type		Numeric	Alphanumeric
Module	3 of 9 Code		X
Width	Industrial 2 of 5 Code	X	
Encoded	Interleaved 2 of 5 Code	X	
	Matrix 2 of 5 Code	X	
	Codabar Code	X	
	Code 11	X	
NRZ	UPC A,B,C,D,E	X	
Encoded	EAN 8, 13	X	

module width.

Table 1 presents a number of popular bar codes and lists them in terms of the encoding technique used and the data encoded. The two encoding techniques specified are module width encoding and NRZ (non-return-to-zero) encoding. Module width encoding is used in most industrial bar codes whereas commercial bar codes commonly use NRZ encoding. The data encoded can be either numeric (0-9 only) or alphanumeric (0-9, A-Z, plus special characters)

The technique used to represent binary data differs between module width encoding and NRZ encoding. In module width encoding, a narrow element (bar or space) represents data whose logic value is zero (0). Data with a logic value of one (1) is printed as a wide element whose width is typically two to three times that of the narrow element. Bar codes which utilize this encoding technique are often referred to as two-level codes due to the use of wide elements and narrow elements in the code structure. Note that there are definite printing transitions from black to white or white to black separating each binary data bit from its neighbors.

The NRZ encoding technique used

commercially in the Universal Product Code (UPC) and in European Article Numbering (EAN) encodes binary data in the reflectivity of the bars and spaces. Here the logic zero (0) data is presented as a reflective surface and the logic one (1) data is presented as a non-reflective surface. Note that there is no printing transition between bits unless the logic state changes. A binary sequence of 1's or 0's may thus be represented by the width of a single reflective or non-reflective element. UPC and EAN codes are sometimes referred to as four-level codes because up to four data bits of the same logic value may be contained in a single reflective or non-reflective element.

The characteristics of the module width and NRZ encoding techniques are summarized in Figure 3. The interaction of the scanner and the code is also presented. Figure 3 shows that the logic state of the scanner is dependent only on the reflectivity of the surface over which it is scanned. It is the decoder which must interpret the time in each logic state and determine both the symbology being scanned and the characters encoded in the symbol. The operation of the scanner and decoder will be discussed in detail in another section of this application note.

FUNCTION	MODULE WIDTH CODING	NRZ CODING
WAND OUTPUT LOGIC LOW "0" LOGIC HIGH "1"	REFLECTIVE (WHITE) NON-REFLECTIVE (BLACK)	REFLECTIVE (WHITE) NON-REFLECTIVE (BLACK)
BINARY DATA ENCODATION LOGIC LOW "0" LOGIC HIGH "1"	NARROW ELEMENTS WIDE ELEMENTS	REFLECTIVE (WHITE) NON-REFLECTIVE (BLACK)
MESSAGE/CHARACTER ENCODATION	SEQUENCE OF NARROW (0) & WIDE (1) ELEMENTS	WIDTH OF BLACK & WHITE ELEMENTS

EXAMPLE
CHARACTER = 1 1 0 0 0 1



Figure 3. Bar Code Conventions.

The third method of categorizing bar code symbologies is by information density, or the number of *message* characters which can be encoded per unit length. This is important to the user because there is often a limit to the amount of space available for a bar code symbol of pre-determined message length. The physical length required for the symbol can be determined by dividing the number of message characters (including checksum character, if used) by the theoretical information density of the symbology and then adding the space required for both start/stop characters and start/stop margins. Note that the inclusion of start/stop characters as part of the printed symbol will yield an actual information density which is less than the theoretical information density often claimed for a symbology. This difference will be larger for symbols with few message characters and smaller for symbols with a large number of message characters.

Information density is commonly segmented into three groupings: high, medium, and low. A high density message is one that holds more than 8 characters per inch;

medium density has a range from 4 to 8 characters per inch; a low density message contains less than 4 characters per inch.

Two factors which influence information density are the code structure and the width or "resolution" (m) of the narrow element or "module". The information density of a given symbology can change by increasing or decreasing the resolution at which it is printed. Module resolution is also commonly separated into three groupings. A high resolution module is nominally less than 0.009 in. (0.23 mm), medium resolution is between 0.009 in. (0.23 mm) and 0.020 in. (0.50 mm), while low resolution is greater than 0.020 in. (0.50 mm). The selection of module resolution is normally dictated by the information density requirements of the application and/or by the printer.

Table 2 presents the information density of six popular industrial bar codes at different module resolutions. Also presented is the information density which would result if start/stop characters were included for a message length of ten characters. A comparison of the two provides an

example of the relationship between the information density commonly claimed for a symbology and the actual information density realized by the printed bars and spaces. Note that start/stop margins have not been included in this analysis.

It is interesting to note that a high information density can be achieved with a medium module resolution and that a medium density is possible with a low module resolution. For example, Interleaved 2 of 5 code has an information density of 9.3 characters per inch when printed with a module resolution of 0.012 in. In fact, when start/stop characters are included, this code can have a higher information density at 0.012 in. module resolution than the 3 of 9 and Codabar codes have at a high, 0.0075 in. module resolution. A medium module resolution is generally recommended if the symbology selected has sufficient information density at this resolution. This will be discussed in greater depth in later sections of the note.

The specific characteristics of six industrial bar codes: Industrial 2 of 5, Matrix 2 of 5, Interleaved 2 of 5, the Alphanumeric 3 of 9, Codabar, and Code 11 are discussed in the following sections of the application note.

The 2 of 5 Bar Code Family

The structure of the 2 of 5 bar code family is one of the simplest of the width-modulated industrial bar codes. There are three well-known members of this family: the Industrial, Matrix and Interleaved. These three codes have the following similarities:

- Two wide elements per five-element character
- Black bars and white spaces

Table 2. Information Density/Module Resolution for Popular Industrial Bar Codes

	Information Density (characters per inch)					
	High Resolution m = 0.0075 in. (0.19 mm) Start/Stop Character		Medium Resolution m = 0.012 in. (0.3 mm) Start/Stop Character		Low Resolution m = 0.021 in. (0.53 mm) Start/Stop Character	
	Without	With⁽¹⁾	Without	With⁽¹⁾	Without	With⁽¹⁾
3 of 9 Code ⁽²⁾	9.8	8.2	5.2	4.4	3.0	2.5
Industrial 2 of 5 ⁽²⁾	10.8	9.5	6.0	5.2	3.4	3.0
Matrix 2 of 5 ⁽²⁾	15.9	13.7	8.3	7.2	4.8	4.1
Interleaved 2 of 5 ⁽²⁾	18.0	16.2	9.3	8.4	5.3	4.8
Codabar Code ⁽³⁾	9.6	8.0	6.1	4.9	3.5	2.8
Code 11	15.9	12.3	—	—	—	—

Notes:

1. 10 character message. Checksum character not included, except for code 11 where one checksum character is included. Start/Stop margin lengths not included.
2. Wide element to narrow element ratio (WE:NE) is 2.2:1 for high module resolution and 3.0:1 for medium and low module resolutions. Intercharacter spaces, where applicable, are assumed to be one module in width.
3. Bar and space widths are in accordance with Codabar code specifications, magnified to the module resolution (m) indicated.

- Numeric character sets (0-9)
- Binary encoding: wide = 1; narrow = 0. A wide element is typically two to three times wider than a narrow element width
- Non-character start/stop, bar/space pattern
- Even-parity character check
- Optional message checksum character

All of these 2 of 5 codes use five binary elements to encode each character. Two of the elements of each character are logic 1s and, depending on the family member, are printed as wide bars and/or wide spaces. The consistent use of two wide elements out of five provides an easy method of character error checking.

Table 3 shows the binary-to-character encoding scheme used by these 2 of 5 family members. It is a weighted binary type with even parity. The least significant bit

Table 3. 2 of 5 Bar Code Character Encoding

Character	LSB 1	2	4	MSB 7	Parity P
0	0	0	1	1	0
1	1	0	0	0	1
2	0	1	0	0	1
3	1	1	0	0	0
4	0	0	1	0	1
5	1	0	1	0	0
6	0	1	1	0	0
7	0	0	0	1	1
8	1	0	0	1	0
9	0	1	0	1	0

(LSB) is located on the left, and the parity bit follows the most significant bit (MSB) on the right. The fact that this code is a weighted binary type allows the decoder to calculate the encoded value, rather than performing a comparison search between decoded bit patterns and those located in memory.

Another common feature of these

code members is the calculation of the optional message checksum character which encodes information about the number, value, and sequence of the characters in the message. The value of the checksum character is determined by the following six step procedure:

1. Identify even and odd positioned characters in the message with the right-hand

message character ALWAYS defined as an even positioned character.

2. Sum the numeric values of the odd positioned characters.
3. Sum the numeric values of the even positioned characters and multiply the total by three.
4. Sum the odd and even totals from steps 2 and 3.
5. Determine the smallest number which, when added to the sum in step 4, will result in a multiple of 10. This number is the value of the checksum character.
6. If Interleaved 2 of 5 code is being used, determine whether the total number of characters (message plus checksum) is odd or even. If odd, add a leading, nonsignificant zero to the message to produce an even number of total characters as required by the symbology.

The specific characteristics of the three 2 of 5 codes, and their differences, are presented in the following sections.

Industrial 2 of 5 Code

The oldest member of the 2 of 5 family is the Industrial 2 of 5 code. Each character is represented by five printed black bar elements, separated by interelement spaces. These five elements create a discrete character used to encode the five binary bits that represent the message character. Each character is separated from the adjacent characters by an intercharacter space. The use of intercharacter spaces makes each character independent or “discrete”. As a result, the Industrial 2 of 5 code and all other codes with intercharacter spaces are termed “discrete codes”. Figure 4 shows the symbol structure of the Industrial 2 of 5 bar code.

MESSAGE = 0 0 2 2

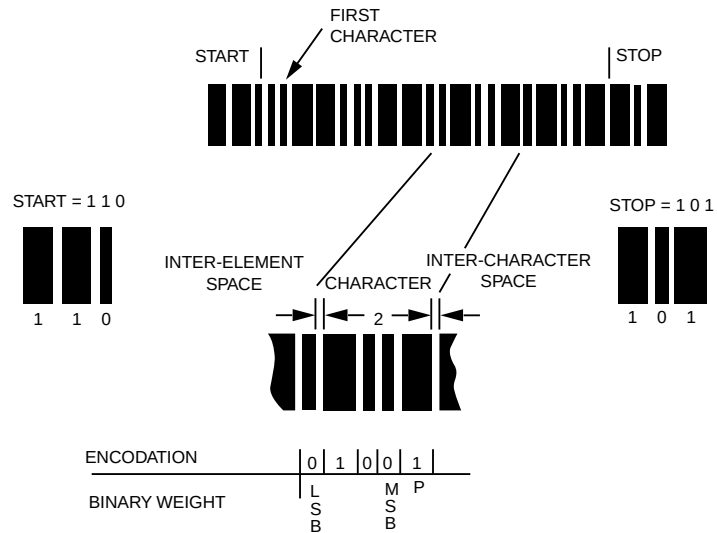


Figure 4. Industrial 2 of 5 Message/Character Structure

The physical length of the symbol is determined by a number of factors. The first is the number of characters in the message. If a checksum is used, one character is added to the message length. The next most important factor is the number of printed modules used to represent a discrete character. Each Industrial 2 of 5 character consists of five bars (three narrow, two wide), four interelement spaces, and one intercharacter space. The interelement spaces, inter-character spaces, and narrow bars, are typically one module wide. The ratio of the wide bar width to the module width sets the total number of modules used to encode the character.

Typically, this ratio is between two and three. The table below illustrates the number of modules used to create a single character when the wide bar (WB) to narrow bar (NB) ratio is 2 or 3.

The next factor influencing symbol length is the number of modules used in the start and stop patterns of the code. The start character is a binary sequence of 110, which is represented as WB,WB,NB. The stop character is a pattern of WB,NB,WB, representing a logic word of 101. Each of these elements is separated by interelement spaces. The start character also has an inter-character space which separates the start sequence from the message.

	WB:NB = 2 Modules	WB:NB = 3 Modules
BS = Interelement space (4X1)	4	4
CS = Intercharacter space	1	1
NB = Narrow bar element (3X1)	3	3
WB = Wide bar element (2XWB:NB)	4	6
Total	12	14

		WB:NB = 2 Modules	WB:NB = 3 Modules
Start	BS	2	2
	CS	1	1
	NB	1	1
	WB (2XWB:NB)	4	6
Stop	BS	2	2
	NB	1	1
	WB (2XWB:NB)	4	6
	Total	15	19

The table above shows the number of modules that result from a WB:NB ratio of 2:1 or 3:1.

These two tables can be combined to determine the total number of modules used to create a message with start and stop characters given the wide bar to narrow bar ratio.

The length of the printed message with the start and stop characters is determined by multiplying the single module width (m) by the total number of modules in the message. The complete symbol length can be determined by adding the length of the start (M1) and stop (M2) margins. The equations shown below can be used to calculate the total symbol length (L) given the WB:NB ratio, the number of characters (N), and the length of the start and stop margins.

$$\text{WB:NB} = 2 \\ L = m(12N+15)+M1 +M2$$

$$\text{WB:NB} = 3 \\ L = m(14N+19)+M1 +M2$$

The conclusion that can be drawn from this analysis is that the total symbol length depends upon the resolution (m) of the module, the WB:NB ratio and its effect on the number of modules per character, and the length of the start and

stop margins. Thus, the highest information density (characters per inch) can be obtained when using a high-resolution module and a wide bar whose length is only two times that of the narrow bar.

Matrix 2 of 5 Code

Higher information density is possible with the 2 of 5 family if information is encoded in both the black bars and the white spaces. Such an encoding technique eliminates the inter-element spaces. Compared to the Industrial 2 of 5, this would eliminate four modules per character, resulting in a 28%-33% information density improvement. The Matrix 2 of 5 code implements this improved efficiency. Each character includes three black bars and two white spaces, plus one intercharacter space. The use of the intercharacter space classifies this code as a discrete type.

The start/stop sequence of the Matrix 2 of 5 code consists of five binary bits that create the word 10000 (WB, NS, NB, NS, NB). The start character also has an intercharacter space to separate it from the first character of the message.

The symbol length of the Matrix 2 of 5 code can be calculated using the equations below. Note that

the wide to narrow ratio is now expressed as a wide element to narrow element ratio (WE:NE) where elements represent either bars or spaces.

$$\text{WE:NE} = 2 \\ L = m(8N+13)+M1 +M2$$

$$\text{WE:NE} = 3 \\ L = m(10N+15)+M1 +M2$$

Interleaved 2 of 5 Code

An even higher information density can be achieved with the elimination of the intercharacter space. The Interleaved 2 of 5 bar code does this by interleaving characters encoded in the bars with characters encoded in the spaces (see Figure 5). The first character at the left side of the message is encoded into the bars immediately following the start character. The second character of the message is encoded into the spaces separating the bars in the first encoded character, thus eliminating the need for the intercharacter space.

The start character consists of four narrow elements representing the binary sequence 0000 (NB, NS, NB, NS). The stop pattern is binary word 100 (WB, NS, NB). The start and stop patterns of the Interleaved 2 of 5 code use fewer modules than those of the Matrix or Industrial 2 of 5 codes, adding further to a higher information density. The symbol length of the Interleaved 2 of 5 Code can be calculated using the following equations:

$$\text{WE:NE} = 2 \\ L = m(7N+8)+M1 +M2$$

$$\text{WE:NE} = 3 \\ L = m(9N+9)+M1 +M2$$

The Interleaved code is termed a “continuous” code because it does not use intercharacter spaces. Its continuous nature and its interleaving of the message characters make the Interleaved code the most complex of the 2 of 5 family to print and decode. The interleaving of characters also requires that an even number of characters be encoded. When the message (including checksum character, if used) contains an odd number of characters, a leading, non significant zero is added to obtain an even number of characters.

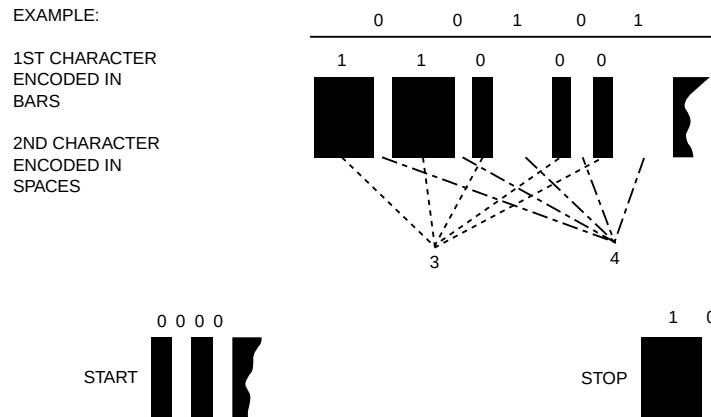


Figure 5. Interleaved 2 of 5 Encodation

The Interleaved 2 of 5 bar code has the highest information density of the entire 2 of 5 family. Figure 6 compares the symbol length of the message “72” for the three 2 of 5 family members. Interleaved is 36%-42% more dense than Industrial and 10%-12.5% more dense than Matrix. Because of this high information density for encoding numerical data, many industries are adopting it as their standard.

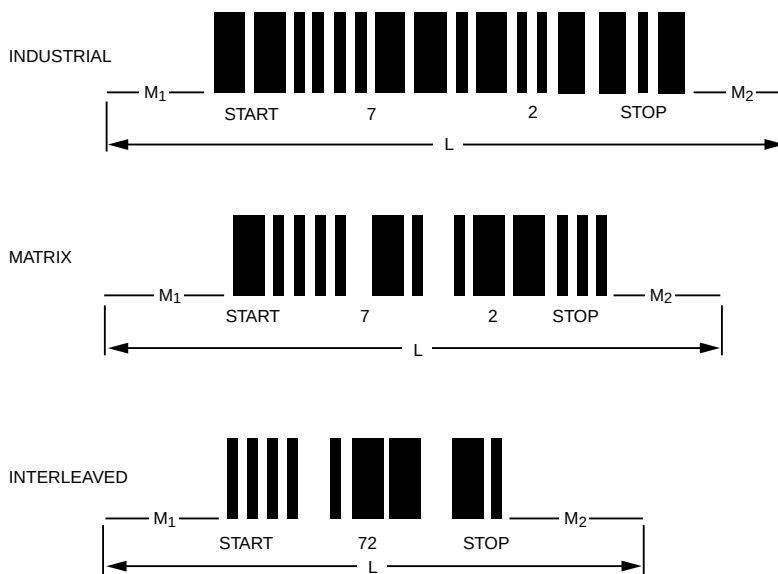


Figure 6. 2 of 5 Symbol Length Comparison

Many inventory and data collections systems currently use both numeric and alphanumeric data to record part numbers and transactions. The 2 of 5 bar code family is capable of encoding only numeric data. Thus, in those instances where alphanumeric data must be encoded, a different code must be selected.

3 of 9 Code

The most popular alphanumeric bar code is the 3 of 9 Code. This code, also referred to as Code 39(1), employs 36 defined numeric and upper case alphabetic characters, seven special characters, and a special stop/start character. The asterisk “*” is used exclusively for the start/stop character.

An example of a 3 of 9 code symbol is given in Figure 7. Both bars and spaces are width-modulated to encode the logic values of the nine binary bits of data. A logic “1” is encoded as a wide element while a logic “0” is encoded as a narrow element. Individual characters are separated by an intercharacter space, classifying this code as a discrete type.

The binary-to-character encoding for the 43 alphanumeric charac-

ters and the start-stop character is presented in Table 4. Note that each character consists of three wide elements (WB,WS) and six narrow elements (NB,NS). This leads to an easy method of character error checking. In addition, note that all but four special characters (\$, /, +, %) use two wide bars in a field of five bars and one wide space out of four spaces.

Note 1. Registered trademark of Interface Mechanisms Inc. The symbology is in the public domain.

In 3 of 9 code, as with the 2 of 5 codes, information density is determined by the number of modules per character and the width resolution of the narrow module. The number of modules per character is influenced by the wide element to narrow element ratio (WE:NE). For high module resolutions, a wide-to-narrow ratio of 2.2:1 is proposed; for medium and low module resolutions, a wide-to-narrow ratio of 3:1 is common.

When a high module resolution is used with a WE:NE = 2.2:1, each character consists of 13.6 modules. This includes an intercharacter gap which is nominally one module wide. For medium and low module resolutions, where WE:NE = 3:1, each character consists of 16 modules. The number of modules in the two asterisks (*) used for start/stop characters is 26.2 for high resolution and 31 for medium and low resolution. These two module sums are used with the module resolution (m) to calculate the length of the bar code symbol. The equations are shown below:

Where:

L = symbol length

m = module resolution (narrow element width)

N = number of message characters, plus checksum character (if used)

$M1, M2$ = margin lengths

High resolution,

WE:NE = 2.2:1

$$L = m(13.6N + 26.2) + M1 + M2$$

Medium/low resolution,

WE:NE = 3:1

$$L = m(16N + 31) + M1 + M2$$

The margin or quiet zone for 3 of 9 code is typically 20 to 30 times the module resolution.

Tale 4. 3 of 9 Code Character Set Encodation

CHAR.	PATTERN	BARS	SPACES	CHAR.	PATTERN	BARS	SPACES
1		10001	0100	M		11000	0001
2		01001	0100	N		00101	0001
3		11000	0100	O		10100	0001
4		00101	0100	P		01100	0001
5		10100	0100	Q		00011	0001
6		01100	0100	R		10010	0001
7		00011	0100	S		01010	0001
8		10010	0100	T		00110	0001
9		01010	0100	U		10001	1000
0		00110	0100	V		10001	1000
A		10001	0010	W		11000	1000
B		01001	0010	X		00101	1000
C		11000	0010	Y		10100	1000
D		00101	0010	Z		01100	1000
E		10100	0010	-		00011	1000
F		01100	0010	.		10010	1000
G		00011	0010	SPACE		10010	1000
H		10010	0010	*		00110	1000
I		01010	0010	\$		00000	1110
J		00110	0010	/		00000	1101
K		10001	0001	+		00000	1011
L		01001	0001	%		00000	0111

* DENOTES A START/STOP CODE WHICH MUST PRECEDE AND FOLLOW EVERY BAR CODE MESSAGE
NOTE THAT * IS USED ONLY FOR THE START/STOP CODE

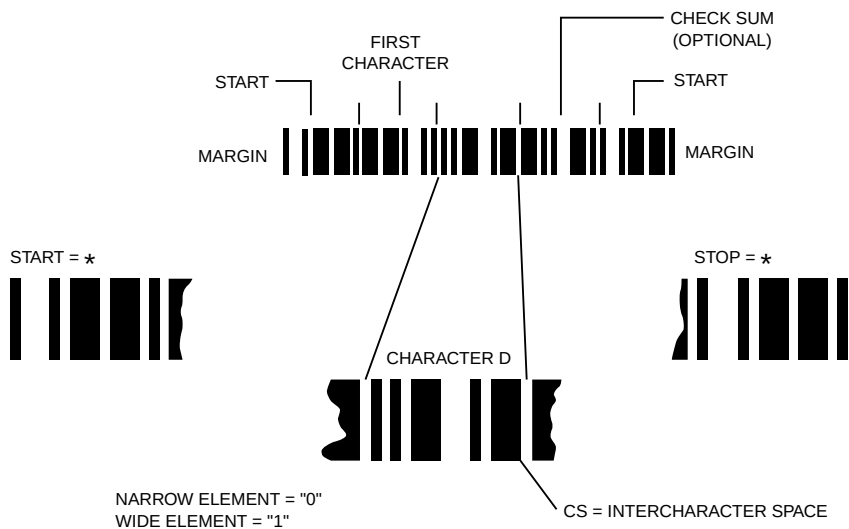


Figure 7. 3 of 9 Message/Character Structure

The 3 of 9 code is commonly used in three different module resolutions corresponding to the desired information density: high, medium, or low. A high module resolution of 0.0075 in. (0.19 mm) results in a high information density of 9.8 characters per inch. Medium information density of

5.2 characters per inch results when a medium module resolution of 0.012 in. (0.3 mm) is used. A low information density of 3 characters per inch occurs when the module resolution is 0.021 in. (0.53 mm). A relative comparison of each of these densities is given in Figure 8.

An optional checksum character may be added at the end of a 3 of 9 code message. The checksum character checks that the correct number and type of data is present, thus providing additional data security. This checksum character is the modulus 43 sum of the assigned value of the characters in the message. The values assigned to each of the characters are presented in Table 5.

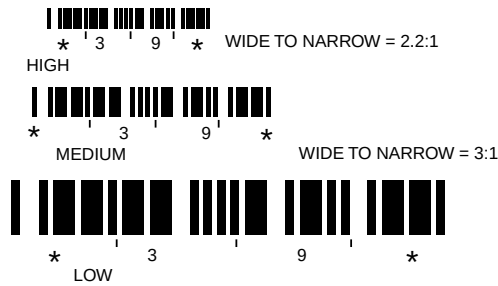


Figure 8. 3 of 9 Code Length

Figure 9 illustrates the simple checksum technique. First, the character values of the message are obtained from Table 5 and added together. This sum is divided by 43, and the remainder corresponds to the checksum character, which is added as the last character in the message. Thus, the message HEDS-3050 becomes HEDS-3050U when a checksum is used.

MESSAGE					HEDS-3050					SUM = 116
CHARACTER	H	E	D	S	-	3	0	5	0	
VALUE	17	14	13	28	36	3	0	5	0	

$\frac{116}{43} = 2, \text{REMAINDER} = 30$
 $30 = U = \text{CHECK CHARACTER}$
 FINAL MESSAGE
 HEDS - 3050U

Figure 9. A Simple Checksum Technique for 3 of 9 Code

The alphanumeric 3 of 9 code and the 2 of 5 codes are the most widely used industrial bar codes. In addition, there are two numeric bar codes which have gained acceptance in more specialized applications. The first of these, the Codabar code, has become common in inventory applications such as library book tracking, blood bank control, and for photofinishing envelopes. Code 11, on the other hand, is sometimes used on printed circuit boards where a very high density discrete bar code is required.

Codabar

The Codabar code is a discrete, width-modulated bar code that provides a character set for encoding numeric data (0-9) plus six special characters (\$, —, :, /, ., +). There are four different sets of start/stop characters (a/t, b/m, c/*, d/e) available for use with this code. This feature allows the

Table 5. 3 of 9 Code Checksum Values

Character	Value	Character	Value	Character	Value
0	0	F	15	T	29
1	1	G	16	U	30
2	2	H	17	V	31
3	3	I	18	W	32
4	4	J	19	X	33
5	5	K	20	Y	34
6	6	L	21	Z	35
7	7	M	22	—	36
8	8	N	23	•	37
9	9	O	24	space	38
A	10	P	25	\$	39
B	11	Q	26	/	40
C	12	R	27	+	41
D	13	S	28	%	42
E	14				

start/stop characters to be used as the key to different data bases. The structure of a typical encoded symbol is shown in Figure 10.

As shown in Figure 10, there are seven binary bits of information encoded in the bars and spaces of each character. There are two bi-

nary 1s, or wide elements, in the field of seven elements for the numeric characters (0-9) and two special characters (\$, —). One binary 1 is encoded by a wide bar while the other is encoded as a wide space. The remaining special characters (:, /, ., +) and the start/stop characters have three binary

1s per character. These are encoded as three wide bars in the special characters and one wide bar/two wide spaces in the start/stop characters. Table 6 presents the complete character set for the Codabar code, showing the encodation of each character.

Unlike the other width-modulated codes, the Codabar code does not use common wide and narrow element widths to encode the logic 1s and 0s in the characters. There are, instead, a total of 18 different widths for bars and spaces specified by the symbology. This structure was designed to account for the printing errors characteristic of certain early printers, leading to printed symbols which could be easily read. Note that it also provided a constant character length, regardless of whether two or three wide elements were used in the character.

The Codabar code is commonly printed at a high module resolution of 0.0065 in. (0.17 mm), the highest module resolution used by any symbology. The information density at this module resolution is 11 characters per inch. When lower information density is allowable, or when printer capabilities necessitate a lower module resolution, the Codabar code recommends symbol magnification in 25% increments. For example, the first magnification results in a module resolution of 0.0081 in. (0.21 mm) and an information density of 9 characters per inch.

Code 11

Code 11 is a discrete, numeric bar code similar to the Matrix 2 of 5 code. There are 11 characters defined for this symbology: numeric characters (0-9) and one special character (—). In addition, a

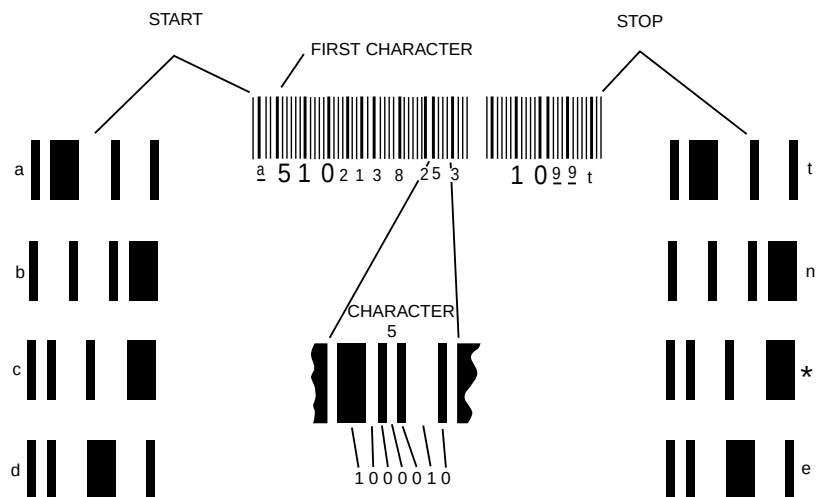


Figure 10. A Typical Codabar Code Symbol

twelfth character (Δ) is defined for use as the start/stop character.

Each character is encoded in five binary bits, three bars and two spaces. Unlike the Matrix 2 of 5 code, not all characters have two wide elements out of the field of five elements. Instead, nine characters (1-8, Δ) have two wide elements out of five, and the other three characters (0, 9, —) have only one wide element out of five. Code 11 is, therefore, not self checking as is the Matrix 2 of 5 code. As a result, no checking algorithm exists which may be applied to each character for character error checking. This, combined with a code structure that allows one printing defect in a character to result in a substitution error, prevents Code 11 from being classified as a self-checking bar code.

The specifications for Code 11 infer that this code should only be used with a high module resolution of 0.0075 in. (0.19 mm), resulting in an information density of 15 characters per inch. The wide element to narrow element ratio is 2.24:1 for characters with

two wide elements and 3.5:1 for characters with one wide element. This unusual structure leads to a constant character length of 0.056 in. (1.42 mm), not including the intercharacter space. The constant character length facilitates printing with certain high module resolution printers.

The use of one, or preferably two, checksum characters is recommended with Code 11 because it is not a self-checking code. The calculation of these checksum characters is rather complicated and will not be presented here. Note that the use of checksum characters will reduce the actual information density realized by the printed symbol. The length of a Code 11 symbol can be calculated by the equation below, assuming an intercharacter space width of one module.

$$L = m(8.5N + 8.5C + 16) + M1 + M2$$

where:

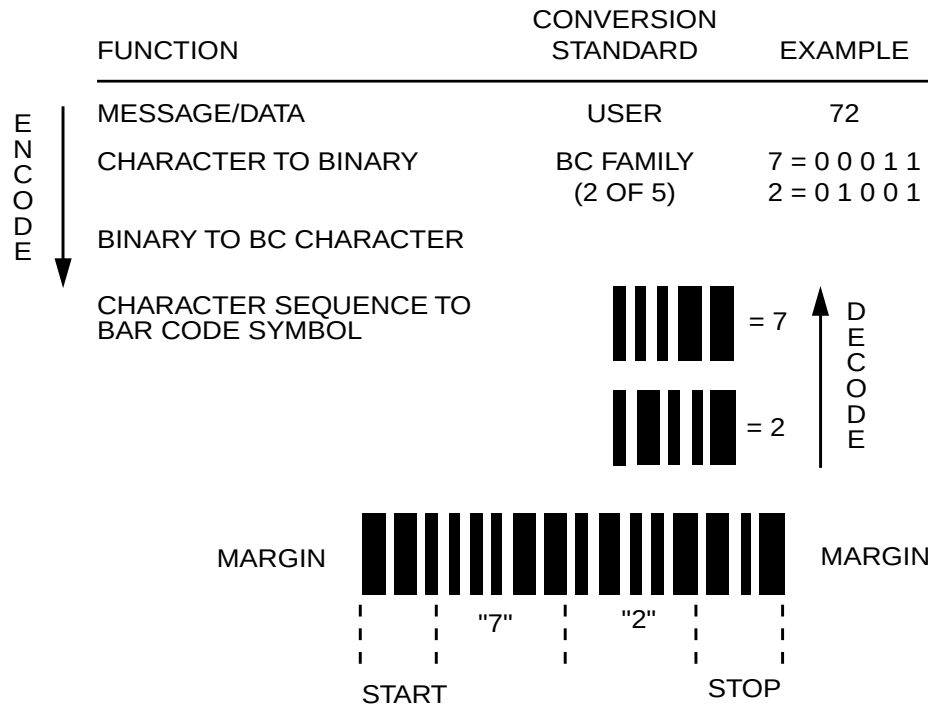
L = symbol length

m = module resolution

N = number of message characters

C = number of checksum characters

$M1, M2$ = start/stop margin lengths

Table 6. Codabar Code Character Set Encodation

For a message length of 10 characters, the length of the printed bars and spaces with one checksum character will be 0.82 in. The actual information density realized is, therefore, 12.2 characters per inch. This compares to a length of 0.74 in. and an actual information density of 13.5 characters per inch for a Matrix 2 of 5 symbol of 10 characters. The Matrix 2 of 5 symbol, in this case, does not include the optional message checksum character. If the checksum character is included, the printed length would be 0.80 in.

Code Selection Summary

Various bar code systems have been introduced to industry; some have become standards while

many others have fallen into disuse. The six bar codes presented here represent the most popular industrial bar codes. A brief summary of standardization activity in the U.S. is shown in Table 7. The agencies or associations listed may be contacted for detailed information regarding these standards.

The two dominant selection criteria which cause a user to choose one code over another are:

1. The type of data to be encoded, and
2. The information density of the symbology

If the data to be encoded is alphanumeric, then the most common

choice is the 3 of 9 code. However, when only numeric data is to be encoded, one of the 2 of 5 family, the Codabar code, or Code 11 may be selected. There are, of course, many other symbologies not discussed in this application note, both numeric and alphanumeric, which the user may want to consider.

The user's application will normally dictate the number of characters to be encoded and the physical area available for the symbol, thus determining the information density requirements of the system. The information density of a particular symbology can be changed by adjusting the module resolution and the wide

Table 7. Code Standardization

Agency or Association	3 of 9 Code	Interleaved 2 of 5	Industrial 2 of 5	Matrix 2 of 5	Codabar Code	Code 11
Dept. of Defense MIL-STD-1189 (LOGMARs)	X					
Material Handling Institute; Automatic Identification Manufacturers (MHI/AIM)	USD-2 USD-3	USD-1			USD-4	
American National Standards Institute (ANSI) Specifications for Bar Code Symbols on Transport Packages and Unit Loads.	X	X			X	
Automotive Industry Action Group (AIAG) (Proposed)	X	X				
Distribution Symbol Study Group (DSSG)	X	X				
American Blood Commission					X	
Uniform Product Code Council, Inc.		X				

element-to-narrow element ratio, as shown in Table 2. There are, however, limitations on how far this process can be taken for a particular symbology while still yielding readable bar codes. Consequently, the information density capability of the symbology must be included as a selection criteria.

Table 8 presents a summary of the characteristics of the six bar codes discussed herein. Refer to Table 2 for information density characteristics of these codes.

Once the bar code symbology has been selected, the user must begin to address the mechanics of generating bar code symbols. This involves issues relating to both the media and the printer. It is important that these issues receive careful consideration as the proper selection of the media and printer are critical to the successful operation of the system.

Symbol Generation

Bar code symbols are created by printing a pre-determined bar/space pattern on a media. There are many printing systems and media available to accomplish this task, or at least so it would appear on the surface. A closer examination will show that there are many optical, mechanical, and operational considerations in selecting both the media to support the bar code symbols and the printing system. The proper selection of these system elements is very important to the successful implementation of a bar code system. In fact, the printer is often the most critical element of the system because it is a large potential source of systematic and random errors.

The requirements placed on the media and printer may be better understood if the basic technology for scanning bar codes is first considered. Briefly, a bar code is scanned by moving a small spot of

light across the bars and spaces. The output of the scanner is determined by the difference in the reflectivity of the bars and spaces. The small size of illuminated area makes the scanner much more sensitive to printing flaws than the naked eye. This places requirements on printer tolerances and inking which are more stringent than those necessary for printing human-readable characters. The composition of the media (spaces) and ink (bars) is also important as this will determine the contrast, or difference in reflectivity, between the bars and spaces at the wavelength of the scanner. An acceptable contrast must be planned for in the system design to ensure that scanner will be able to differentiate between bars and spaces. It is worthwhile noting that the contrast for the scanner may be much different than the contrast perceived by the human eye. For example, a symbol clearly visible to the eye may be invisible to some scanners. This

Table 8. Summary of Bar Code Characteristics

Characteristic	3 of 9 Code	Interleaved 2 of 5	Matrix 2 of 5	Interleaved 2 of 5	Codabar Code	Code 11
Character Set	Alpha-numeric	Numeric	Numeric	Numeric	Numeric	Numeric
Number of Characters ⁽¹⁾	43	10	10	10	16	11
Number of Bits per Character	9	5	5	5	7	5
Number of Element Widths Used	2	2	2	2	18	3
Information in both Bars and Spaces	Yes	No	Yes	Yes	Yes	Yes
Discrete (Independent Characters)	Yes	Yes	Yes	No	Yes	Yes
Self-Checking	Yes	Yes	Yes	Yes	Yes	No
Checksum Character	Optional	Optional	Optional	Optional	None	Recommended

Note: Not including start and stop characters.

phenomenon precludes the use of visual inspection alone as a means of estimating contrast for scanning systems.

The following section will discuss the optical and mechanical specifications to be considered when selecting a suitable media and printing technique. Some operational considerations in the selection of printing equipment or pre-printed labels are also presented. A detailed discussion of bar code scanners will be presented in a later section of this application note.

Media Selection

Bar code symbols can be printed on a wide variety of media. The most commonly used media in industrial applications are adhesive labels, cards, and documents. Since the media is an optical storage device, optical characteristics should dominate the selection considerations. The most important optical specifications to consider are the surface reflectivity of the media at a specific optical wave-

length and the radiation pattern. A third optical parameter to consider is the transparency, or translucency, of the media. In addition to the optical characteristics, there is one mechanical property of the media which must be evaluated — durability. It is important that the media selected be durable enough for the application or that plans are made to cover the media with a protective coating.

The surface reflectivity of the media is defined by the amount of light reflected when an optical emitter irradiates the media surface. Optimally, the media should reflect between 70% and 90% of the incident light. A white media is commonly used to achieve this high reflectivity over a wide range of wavelengths. Consequently, the media reflectivity is given the symbol R_w .

The optical pattern of light that leaves the media surface describes the reflected radiation pattern. A shiny, or specular surface will result in a narrow

radiation pattern whereas a dull, or matte surface will provide a diffuse or broad pattern. Media which have a narrow radiation pattern should be avoided because this may cause operational problems for the scanner. Specifically, the intense reflected light at near perpendicular angles may saturate the scanner electronics while the mirror-like reflection at large scan angles may provide little light back to the scanner, making the media look like a bar instead of a space. A dull, or matte surface is recommended to ensure a radiation pattern which will be acceptable to the scanner over the range of scan angle.

Reflectivity and radiation pattern can be measured by a surface reflectivity meter. Such instruments are manufactured by the Macbeth Division of EG&G and by Photographic Sciences. A lower cost solution to the reflectivity meter can be created by using optical reflective sensors manufactured by Agilent Technologies. Figure 11 shows a circuit which uses a HEDS-1000 reflec-

tive sensor, an operational amplifier, and a voltmeter to measure reflectivity at the 700 nm wavelength of the sensor. Note that 700 nm is the wavelength used by many visible red hand-held scanners, including Agilent Technologies' HEDS-30XX series of wands. A similar optical sensor with a near-infrared wavelength, compatible with Agilent Technologies' HEDS-32XX high resolution wands, is also available upon request.

The circuit described in Figure 11 converts the reflected 700 nm optical signal into a voltage which can be measured by the voltmeter. The system can be easily calibrated by using a well specified diffuse optical reflector, such as Kodak 6080 reflective paint, to set a 0-1 V signal for 0-100% reflectivity. The calibration procedure begins by zeroing the meter when the sensor is not pointed toward a surface (zero reflectivity). The sensor is then placed at a distance of 4.27 mm from the Kodak 6080 painted surface and the gain control is adjusted to read 0.99 volts. Once calibrated, the meter will provide reflectivity measurements for any diffuse media. If a shiny media is used, the calibration procedure is invalidated and the reflected optical signal may exceed 100%.

The radiation pattern of the reflected light can also be determined using the surface reflectivity meter presented in Figure 11. To accomplish this task, the surface should be placed perpendicular to the sensor at the distance which results in the maximum reflected signal (approx. 4.27 mm) The surface plane of the media is then rotated about an axis perpendicular to the optical axis of the sensor, main-

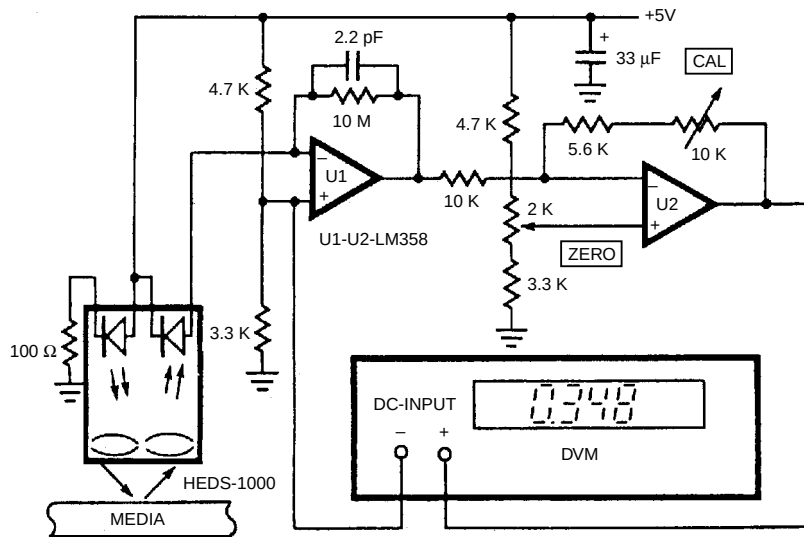


Figure 11. 700 nm Micro Reflectometer

taining a constant distance between the sensor and the point at which the emitter is focused on the surface. As the surface is rotated through an arc, the variation in output signal versus angle of rotation will describe the radiation pattern.

The other optical characteristic to be considered is the transparency, or translucency, of the media. If the media is too transparent, the material underneath the label, card or document will affect the reflectivity (R_w). If the underlying surface contains printed material or is dark in color, the media's reflectivity will be adversely affected. Highly transparent paper such as vellum, lightweight paper, and low weight computer paper should, therefore, not be used. Where the application dictates the use of any of these media, it is recommended that a highly reflective white surface be placed behind the media prior to scanning.

A second phenomenon, paper bleed, also occurs when a trans-

parent or translucent media is used. This phenomenon is caused by the scattering of incident light rays within the media, or from the underlying surface. Some of this scattered light will be detected by the scanner, thereby adding to the light reflecting off the media's surface and resulting in a larger total reflected signal. However, as the scanner approaches the edge of a bar, some of this scattered light will be absorbed in the ink before it can be reflected back to the detector. As a result, the reflectivity of the media will begin to drop off before the bar edge is reached. This optical effect tends to make the bars appear larger and the spaces narrower than they were actually printed. Paper bleed is, therefore, a potential source of systematic error.

The systematic error introduced by paper bleed is relatively constant in magnitude for a specific media. Its effects are, therefore, more pronounced when high module resolution bar codes are used because the error will be a larger percentage of the module width.

This is particularly true for certain photographic papers commonly used to print high module resolution symbols. In general, factors that influence paper bleed are the rag content, the type of binder used, the thickness of the media, and the media's transparency. Paper bleed can be minimized by using heavyweight stock with a high rag content.

The final consideration in the selection of the media is durability, or how many times the wand can be moved across the surface without degrading the reflectivity of the media, smearing the bars, or abrading the symbol. When evaluating the media durability required by the application, the user should consider the number of times that the symbols will be scanned during their lifetime and the severity of the environment that the symbol will be exposed to. If the expected number of scans is less than 100, and the environment is benign, then heavyweight paper with a smooth surface texture may be used. In applications where the symbol will be exposed to adverse environments (dirt, grease, temperature extremes, weather, etc.) or where over 100 scans are probable, the symbol should be protected with a transparent coating which is less than 0.25 mm (0.01 in.) in thickness. Suitable coating materials include lacquer spray, clear plastic laminate, polypropylene film, matte acetate film, and polyester film. A matte surface on the coating material is preferred to avoid the specular problems previously discussed. If shiny coatings must be used, a degradation in first read rate should be anticipated.

One alternative to protective coatings is the use of vinyl or

polyester media. Albeit more expensive than paper, these media offer very good durability plus a great tolerance to cleaning solutions that might be used to remove dirt and dust from the symbol.

In summary, reflectivity, radiation pattern, transparency/translucency, and durability must all be considered when choosing between the media which are feasible for the user's application. When paper is used as the media, heavyweight stock with a high rag content, a matte finish, and a smooth surface texture is recommended. The media should be covered with a protective coating if it will be subjected to harsh environments or scanned a great number of times. If the bar code system will include symbols printed both on control documents and labels, there should be optical consistency between these media to ensure that a similar scanning read rate is achieved.

Once the media has been selected, there are several printing systems which can be used to transpose the bar/space pattern onto the media. These systems have different capabilities in terms of module resolution and print quality which must be considered in the system design.

Printing Systems

Data storage occurs in a bar code system when a printing mechanism deposits ink on the media to form a series of bars (ink) and spaces (media). There are a wide variety of printing techniques which are capable of producing bar code symbols. Some of these processes are oriented toward applications which require an extremely high throughput of la-

bels and/or forms while others are capable only of low to moderate throughput. Table 9 shows a matrix of impact and non-impact printing systems.

The commercial printing processes listed above (letterpress, lithography, offset, gravure, flexography) have been used for many years to inexpensively print bar code symbols on packages, containers, and cartons. Perhaps the most widely observed symbols generated by these processes are the thousands of UPC/EAN symbols printed on consumer packages. Commercial printing can also be used to produce large volumes of pre-printed symbols for use in industrial applications. Lithography and offset are the more commonly used techniques for this purpose.

Large volumes of pre-printed bar code symbols may also be produced by ink jet, laser, and electrostatic printers. These printers are generally computer-controlled page printers and are very expensive.

A large percentage of the industrial applications for bar codes require low to moderate volumes of bar code symbols and, in many cases, also require that the symbols be printed on demand. The most commonly used printers used in these applications are formed character and matrix character impact printers. Thermal printers, while capable of printing bar codes, are generally not used due to readability problems. The more popular impact printing techniques will be described below.

Formed character printers, both rotating drum and daisy wheel,

Table 9. Printing Techniques

	Impact		Non-Impact	
	Formed Character	Matrix Character	Formed Character	Matrix Character
Low/Moderate Throughput	Drummer Daisywheel	Dot Matrix NxM (Typically 5 x 7)		Thermal
High Throughput	Letterpress Lithography Offset Gravure Flexography			Ink Jet Laser Electrostatic

are capable of producing high quality bar code symbols. “Drummer” printers and daisywheel printers both form medium/low module resolution symbols by printing one bar at a time. Each bar, wide or narrow, is printed with the strike of a single hammer and the sequence of wide or narrow bars/spaces is determined through programming. This process enables the printer to print either discrete or continuous bar codes. Note that the “drummer” print wheel or daisywheel may need to be changed to print different bar code symbologies.

The “drummer” mechanism uses a different approach to print high resolution symbols. As shown in Figure 12, print wheels for high module resolution print the symbol character-by-character, not bar-by-bar. This results in well defined characters but also produces loosely defined inter-character process.

Another difference between the “drummer” and daisywheel techniques is that daisywheel printers are capable of printing both documents and labels where the “drummer” printers can only produce labels. This enables the daisy wheel printer to satisfy a wider range of printing needs, not limited to bar code labels.

A second printing technique capable of printing bar codes on both labels and documents, as well as printing general purpose, non-bar coded documents, is applied in dot matrix impact printers. These printers are becoming increasingly popular for printing bar codes because of their flexibility and low cost. However, not all dot matrix printers can print within the tolerances required to produce readable bar code symbols. Only those printers with a graphics capability should be used and, among these, the ones which offer bar code printing as a graphics option are preferred.

As shown in Figure 13, a dot matrix impact printer uses a printhead containing a bank of wires that strike the paper through an inked ribbon. This type of printer creates a narrow bar by printing a set of overlapping dots. A wide bar is produced by printing a series of overlapping narrow bars. The use of overlapping dots results in bar edges which are not as well defined as those characteristic of formed character printers.

The module resolution printing capability of dot matrix printers is limited by the width of the wire hammer and by the thickness of

the ribbon. Most of the wires used in currently available dot matrix printers are between 0.010 in. (0.25mm) and 0.018 in. (0.46 mm). When these hammers strike an inked nylon ribbon, the thickness of the ribbon and bleeding of the ink can cause a wire of 0.014 in. (0.45 mm) in diameter. This effect is positive in that it contributes to the formation of a solid bar; however, it also limits the dot matrix technology to printing medium/low resolution symbols.

A comparison of “drummer” printers and dot matrix printers leads to some interesting tradeoffs. The “drummer” mechanism provides better bar edge definition and is capable of printing symbols with high module resolution. However, it is limited to producing only labels. Dot matrix printers, on the other hand, are more flexible since they can print both labels and documents and are also less expensive. They are, however, limited to producing only medium/low module resolution symbols.

Where medium or low resolution labels are required, either the “drummer” or dot matrix printing technique may be used to produce easily scannable bar code symbols. In fact, the print quality is much

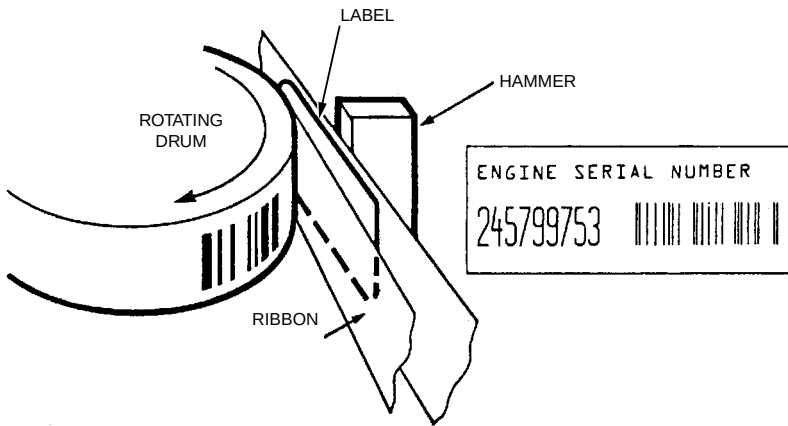


Figure 12. "Drummer" Print Mechanism

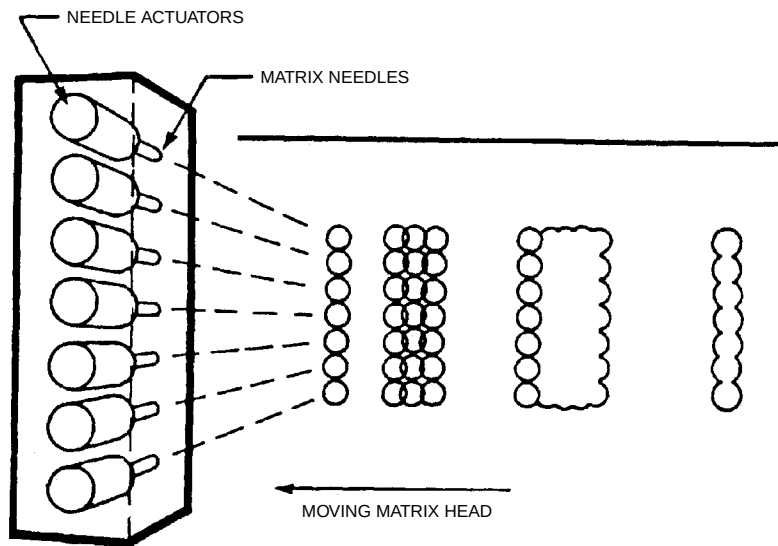


Figure 13. Dot Matrix Print Mechanism

more important to the scannability of the symbol than the printing technique used.

Print Quality

The print mechanism and the ink together determine the quality of the printed symbol. Assuming the printer is capable of the module resolution desired, the major factors influencing quality are:

- Ink Spread/Shrink
- Ink Voids/Specs
- Ink Smearing
- Ink Non-uniformity
- Bar/Space Width Tolerances
- Edge Roughness

All of the above factors are potential sources of systematic errors which are constant from element-to-element and character-to-character and of random errors which are not constant. These errors must be closely controlled to ensure that the symbol will be easily scannable. It is particularly important to limit random errors, as will be discussed in the derivation of decodability in a later section.

The application of ink to the media is a potential source of many errors, as indicated above. The underlying causes for such errors

involve a complex interaction of the print mechanism, the ink, and the media. Table 10 presents the predominant inking errors, listing their primary causes and the type of error which generally results.

The amount of ink spread or ink shrinkage which occurs is determined by the condition of the ribbon and the hammer pressure. Ink spread will result in wider bars and narrower spaces whereas ink shrinkage will have the opposite effect. In addition, both ink spread and ink shrinkage may cause degradation in the bar edge definition. Figure 14 shows three photomicrographic samples of labels printed on "drummer" printers, clearly showing these effects.

As a comparison, Figure 15 presents a photomicrographic sample of a label produced by photolithography, a process which provides excellent inking and bar edge definition.

Ink voids and specks, apparent in Figures 14 and 15, are characteristic of any printing process. If the ink void or speck is large enough, then it is possible for the scanner to recognize the transition across the void/speck as a bar or space. This will lead to the creation of an invalid character and, assuming well-designed software, a no-read. However, the problem is only a temporary one as there is a good chance that the same void/speck will not be encountered on the second scan and that a good read will result. The effects of ink voids and specks can be minimized by keeping them small relative to the module resolution.

Ink smearing and non-uniform inking may also lead to poor read rates. Ink smearing is a problem because it may cause a narrow bar to appear wide, a wide space to appear narrow, or, in the case of high module resolution codes, a narrow space to become too small to be recognized. Consequently, invalid characters can be sensed by the scanner with a mis-read resulting. As with ink voids and specks, this error is typically random so a good read can occur on a second or third scan. Non-uniform inking can lead to a similar difficulty if the inking across the bar is so poor that the scanner does not see a sufficient drop in reflectivity and, therefore, does not recognize the presence of the bar. Once again, a good read may result by scanning a different section of the symbol.

The various inking errors, combined with the characteristics of the print mechanism, will determine the bar/space width tolerances that can be maintained when printing bar code symbols. These tolerances may be specified by the printer vendor or may be empirically measured using a toolmaker's microscope on some sample symbols. As a general rule, the combined mechanical and inking errors characteristic of a printer will be relatively constant, regardless of whether a wide or narrow element is being printed. A larger percentage error will, therefore, occur if the module resolution used is the highest available for the printer. This could lead to a more severe degradation in performance than if a lower module resolution was used. It is important to overall system performance that the printing tolerances be maintained within the limits specified by the symbology, particularly the wide element to

Table 10. Inking Errors

Error	Cause	Type
Ink Spread	Absorptive Paper Over-Inked Ribbon Too Much Hammer Pressure	Systematic
Ink Shrinkage	Worn-out Ribbon Too Little Hammer Pressure	Systematic
Ink Voids and Specks	Dirty Print Head Dirty Paper Defective Ribbon Defective Print Head	Random
Ink Smearing	Ink Not Cured Poor Wetting of Paper	Random
Non-Uniform Inking	Dirty Print Head Mechanism Not Adjusted	Random

narrow element ratio specification.

Edge roughness is also determined by the combined effects of inking and the printing technique. Rather than being discussed separately, edge roughness can be included as one of the factors determining bar/space width tolerances. In effect, the scanner will sense a different bar width depending on which part of the bar it passes over. Edge roughness is a common error in symbols printed with dot matrix printers. However, the module resolution is generally large enough to make this a small percentage error. The readability of the symbol is, therefore, not generally degraded.

After discussing the major factors influencing print quality, there still remains one factor which has a significant influence on the readability of a symbol. This is an optical parameter commonly referred to as print contrast.

Print Contrast

As mentioned in the introduction

to the section on symbol generation, the output of a scanner is determined by the difference in the reflectivity of the bars and spaces. Consequently, one optical characteristic of the symbol which must be evaluated is the interrelationship between the reflectivity of the media (spaces) and the ink (bars). This relationship, commonly referred to as the print contrast signal (PCS), is defined by the equation below:

$$PCS = \frac{R_w - R_b}{R_w} \times 100\%$$

where:

R_w = reflectivity of the media (spaces)

R_b = reflectivity of the ink (bars)

Good scannability of a bar code symbol is obtained when the PCS is greater than 70%. As stated in the media section, the minimum reflectivity of the media (R_w) should be 70%. If R_w is at the minimum recommended 70%, R_b must be less than 21% to achieve a PCS of 70%. Consequently, if $R_w > 70\%$ and $R_b < 21\%$, an adequate PCS will be certain. There



14a. Excellent Print Quality



14b. Good Print Quality



14c. Poor Print Quality (Poorly Inked Ribbon)

Figure 14. Photomicrographs of "Drummer" Printed Labels



Figure 15. Photomicrograph of Photolithographic Label

are, of course, other combinations of R_w and R_b which will result in a PCS above 70%.

It is apparent that either R_w or R_b must be controlled in order to provide an adequate PCS. Although media selection is very important, it is generally more practical to control the reflectivity of the ink. When a new ribbon is used, the reflectivity of the bars should be between 4% and 15%. Inking uniformity and ink shrinkage should be monitored over ribbon life to ensure that an adequate print contrast is maintained.

As with any optical measurement of reflectivity, the value obtained for PCS is only valid for the wavelength specified. It is, therefore, important to measure PCS at a wavelength which is at, or near, the wavelength of the scanner being used. If the scanner has an infrared emitter, then carbon based inks must be used to obtain adequate PCS. For dot matrix printers, OCR ribbons are recommended to achieve this contrast. Dye based black inks, on the other hand, will provide adequate contrast for visible red and near-infrared emitters, but not for infrared emitters.

If colored symbols are desired, then the bars should be printed with a color having a shorter visible wavelength (brown, blue, purple, etc.) and the media, if non-white, should be a color which contains some red content (red, orange, etc.). Only visible red emitters may be used with colored symbols.

The previous sections on printing systems, print quality, and print contrast were intended to provide a basic understanding of the issues underlying the selection of bar code printers and/or pre-printed labels. The next section will bring these issues together in a discussion of the considerations for selecting a bar code printing system.

Printer Selection

Perhaps the first thing to consider in the selection of a bar code system is the information flow which determines the content of the symbol. If the application requires bar code symbols which are sequentially numbered or pre-assigned, then it would be possible to use one of a variety of preprinting processes. Other applications, however, may involve data bases which are continually updated and, as a result, the content of the symbol may not be known until shortly before it is needed. In these cases, the symbol must be printed on-demand at a location near the site where it is to be used.

In situations where symbols may be pre-printed, the user has many choices, as indicated below:

1. Commercial printing.
2. Outside vendors of pre-printed labels.
3. In-house pre-printing using a computer controlled page

printer, dot matrix printer, or formed character impact printer.

The choice between the above alternatives is dependent upon type of media (label, card, or document) and the volume of symbols required. If a large volume of labels or cards are required, then commercial printing may be appropriate. Computype and Data Composition are two of the many vendors of pre-printed symbols. Alternately, a computer controlled page printer may be used to print high volumes of labels or documents in-house. One such printer is the Hewlett-Packard 2680 laser printer.

On the other extreme, when a small volume of pre-printed labels is required, it may be economically advantageous to purchase pre-printed labels from a printer vendor or distributor who offers this service. Scanmark (a Division of Electroprint, Incorporated), is one example of a printer vendor who provides this service.

In the middle ground, where a low-moderate volume of labels or documents is required, in-house pre-printing using a "drummer" or dot matrix printer may be economically justifiable. In choosing between these two printing techniques, the module resolution required, the type of media (label or document) used, and other non-bar code printing needs should be considered. If high resolution labels are required, a "drummer" printer should be selected. Scanmark and Intermec are the two primary vendors of these printers. If medium or low resolution labels are required, either type of printer may be used. The "drummer" printers will generally provide better quality symbols

while the dot matrix printers are less expensive and also have the flexibility of being used for general purpose printing. Where bar coded documents are required, a dot matrix printer should be selected since "drummer" printers are only capable of printing labels. When selecting a dot matrix printer, both line printers and single hammer serial printers should be considered. Single hammer serial printers are generally less expensive and have lower throughput. Hewlett-Packard's Factory Data Printer (Model 2631G, Option 200) is one example of this type of printer.

The second general category of applications are those where the symbols must be created real-time, on-demand. The printers most commonly used in these applications are "drummer" printers and dot matrix printers. The considerations for selecting between these printers are similar to those in selecting a printer for pre-printing, except that a lower throughput printer may be acceptable. These considerations are summarized in Table 11.

Dot matrix printers are often selected when medium or low resolution symbols are to be printed because of their lower cost, greater flexibility, and good print quality. Figure 16 shows some representative dot matrix printed symbols which were printed on a Hewlett-Packard Factory Data Printer.

Once the printer has been selected, maintenance and quality control procedures should be planned to ensure that good quality symbols are produced on a continuous basis. These procedures should include cleaning, ribbon changing, and an on-going

record of print quality. The scannability of the symbols can be checked by using a simple reader or by using more sophisticated verifiers. Maintenance and quality control must be taken seriously because a breakdown in print quality can make the entire bar code system non-operational.

Media/Printer Summary

The media selected to support the bar code symbol and the printing system used to deposit the ink (bars) onto this media are the most critical elements in the design of a bar code system because of the large systematic and random errors which may be introduced into the system. The application will generally determine the type of media to be used (label or document), the module resolution required to achieve the desired information density, the volume of labels or documents needed, and the printing system which is both practical and economically justifiable. The designer's contribution to system performance will be in the selection of the paper (or other) stock used for the label or document, the protective covering (if any), the ink, and the printer. It is these more detailed decisions that will determine whether high quality

symbols of adequate print contrast can be produced repeatably, and scanned successfully.

The issues involved in the selection of the scanner and decoder were interwoven in the discussion of the media and printing system due to the interaction of the symbol's module resolution and wavelength. The following section will present the operational considerations and selection criteria for the scanner in greater detail. Issues involving the operator and decoder will also be discussed.

Data Entry

The data stored in a bar code symbol is retrieved by the movement of an optical scanner across the symbol, or vice versa. The relative movement of the scanner and symbol can be accomplished automatically, as in a conveyor system, or by a human operator. When human involvement is required, the operator also becomes an important part of the data retrieval system. Once the data has been retrieved, it must be interpreted by a decoder, error-checked, and transmitted to the host system.



Figure 16. Dot Matrix Printed Symbols (Reduced)

Table 11. Printer Selection Considerations for On-Demand Applications

Resolution	Media	Printer(s) Available	Comments
High	Labels	"Drummer printer"	Character-by-character symbol formation One code per drum
Medium or Low	Labels	"Drummer printer"	Bar-by-Bar character formation More expensive Very good quality
		Dot Matrix Printer	Good quality Less expensive More flexible
Medium or Low	Documents or Labels and Documents	Dot Matrix printer	Good quality Combined text and bar code symbols

The performance of the data entry system is generally described in terms of first read rate and substitution error rate. The ability of the system to achieve high read rates and low substitution error rates will depend on the design and placement of the symbols, the level of operator training, the scanner selected, the decoding algorithm, and all of the factors discussed in the previous sections: media, print quality, and print contrast.

This section will discuss the operational considerations and selection criteria which apply to the three elements of the data entry system: the operator, scanner, and decoder. The potential sources of systematic and random errors will be presented and the importance of these errors, along with those contributed by the printing system, will be discussed.

The Operator

The presence of an operator is required in many data collection applications. The two primary situations are those in which an operator must go to the product, menu, document, or other item to scan the symbol with a hand-held scanner and those in which it is most convenient, or cost effective, for an operator to use a hand-held scanner or to pass the item/symbol in front of a fixed scanner. Whenever an operator is involved, there are human factors considerations in the system design and potential human errors introduced. To simplify the discussion, only those situations where a hand held scanner is used will be considered. Issues which pertain to systems where the operator moves the symbol are similar, but not identical.

Perhaps the first consideration

should be the motion of the human hand. It is obvious that the operator must be able to scan across the entire symbol, including margins, in order to obtain a successful read. The placement of the bar code symbol should be designed to facilitate this action. Consequently, the symbol should be located so that it can be easily reached and scanned. This means that awkward hand movements, arm overextensions, contorted positions, and potentially hazardous positions should not be part of the scanning operation. The second aspect of human hand motion that should be considered is the tendency to move the scanner along an arcing, or curvilinear, path. The height of the printed bars should be greater than 0.2 inches, or preferably 0.3 inches, to accommodate this motion. Bar height may need to be even higher if a particularly long symbol is to be scanned.

Also important to successful operation is a limited amount of operator training. The operator should be instructed how to hold the scanner, how to scan the symbol, and how to recognize a good read. The "good read" feedback may be provided by the decoder or host computer via a beeper, indicator, or display readout. It may take several hundred scans for the operator to gain proficiency in the operation of the scanner.

Despite training and operator experience, human errors will occur. If severe enough, such as a failure to scan the entire symbol, a no-read will clearly result. More subtle errors such as changes in velocity or angle while scanning, will add to other random errors present in the system. This will make the decoder's job more difficult and, depending on the

magnitude of the total error and decoder design, may contribute to a no-read or a substitution error. Note that substitution errors are very unlikely with a well designed decoder if the code is self-checking or if a checksum character is used.

When selecting between scanning and decoding systems, the relative "friendliness" to a trained operator should be considered. This "friendliness" is a function of many technical parameters which will be discussed in the next section.

Scanners

The binary data encoded in the wide or narrow bars and spaces of a bar code symbol is extracted by an optical system which generally consists of an emitter, a detector, and an optical lens. The emitter scans a beam of light over the symbol while the detector simultaneously responds to changes in the reflected light levels. The photodetector produces a high output current when the reflected signal is large, such as when passing over a space, and a low output current when the reflected signal is low. A low reflected signal will occur if the beam is over a bar or if the scanner is pointed into free space.

The shape of the analog waveform which results will be determined by the print quality (print contrast, bar edge definition, voids/specks, uniformity, etc.), by the widths of the bars and spaces, and by the scanning motion. An optimal waveform will occur if a clearly printed symbol with a high PCS and sharp bar edge definition is scanned at a constant velocity. Although this is not realistic, the factors which influence the analog waveform should be understood because this waveform will be con-

verted to a digital signal for processing by the decoder. The ability of the digitizing circuit to differentiate between bars and spaces and to accurately represent their physical widths in the time domain will depend on the quality of the analog waveform and, of course, also on the design of the digitizing circuit.

There are many different types of bar code scanners which implement the basic optical system described above in different ways. The selection of a specific scanner system requires consideration of the operational needs of the application and the characteristics of the scanner.

In general, scanners can be categorized as either stationary scanners or hand-held scanners. Stationary scanners are further subdivided into moving beam systems which use a rotating mirror to automatically sweep a light beam back and forth across a symbol and fixed beam systems which require the symbol to be passed in front of the scanner at a relatively constant velocity. Hand-held scanners are typically wands (or light-pens) but can also be hand-held laser scanners.

The user's application generally dictates whether a stationary scanner or a hand-held scanner is needed. Operational considerations which will influence the selection between these two general categories of scanners are the location of the symbol, the frequency of scans, the point(s) of data entry, and the level of automated manufacturing and/or material handling. Perhaps the most common application for stationary scanners is on conveyor systems or automated assembly lines where the items to be

scanned pass in front of the scanner at a rapid pace. Hand-held scanners, particularly wand scanners, enjoy the advantages of being more flexible and also lower in cost. These devices are generally preferred in applications such as those listed below:

1. Labor intensive assembly, repair, test, and lot processing operations where scanning is a small part of the overall activity.
2. Applications in which the position of the symbol may change, requiring an operator to locate and scan the symbol.
3. Applications in which it is more practical for the scanner to go to the symbol, rather than vice-versa. Included here are the many applications for portable terminals with wands attached.
4. Applications in which human judgement must be applied to determine what symbol should be scanned or when to scan.
5. Applications in which the scan frequency is low or where the cost of an automated system with stationary scanners cannot be justified.

Specific applications for wand scanners include: inventory control, identifying assemblies in service, repair, test, and manufacturing environments, work status or equipment status reporting, equipment check-out, fixed asset accounting/tracking, remote order entry, and the programming of intelligent instruments. The remainder of this section will discuss the technical and operational considerations important in the selection of a bar code wand.

The most important selection criteria for a bar code wand can be segregated into optical parameters, electrical characteristics,

and resolution:

Optical Parameters

Spot size (or aperture size)

Wavelength

Depth of field

Electrical Characteristics

Analog or digital output

Supply voltage(s)

Resolution

Optical Parameters

Optical systems used in wand scanners generally have either an apertured emitter or an apertured detector. Apertured emitter systems project a focused light spot on a symbol and use a detector with an overlapping image area to collect reflected light. Systems with an apertured detector flood-light a small area of a symbol with light, using a focused-detector image to sample the light reflected from this area. The size of the spot produced by the former approach is roughly equivalent to the size of the aperture in the second approach.

Spot size (or aperture size) determines the analog signal modulation experienced as the wand is passed over a series of bars and spaces. As shown in Figure 17, the spot size (or aperture size) should be smaller than the module resolution (narrow element width) of the symbol in order to obtain a clearly defined analog signal. Signal clarity is important to system operation because a clearly defined analog signal will be more accurately processed by the digitizing circuit. As a result, the bar/space width information presented to the microprocessor for decoding will more precisely replicate the printed bars and spaces. Note that voids and specks must be maintained at a size significantly smaller than the spot size (or aperture size) to prevent no-reads.

For an analog system, the spot size (or aperture size) can be determined by measuring the square wave modulation transfer function that occurs when using a USAF 1951 test pattern or an NBS 1963A target. Typically, modulation is specified for a certain density of equal width bars and spaces in terms of line pairs per mm. This is the technique generally used for specifying analog wands.

The second important optical parameter is the wavelength of the emitter used. Most wands contain an LED emitter which has a wavelength of either 633 nm, 700 nm, 820 nm, or 930 nm. As discussed previously, the wavelength of the emitter is important in determining the PCS of the symbol. In general, infrared emitters (930

nm) require the use of carbon based inks while visible red emitters (633 nm or 700 nm) can be used with carbon based inks, dye based black inks, or colored inks. Near-infrared emitters (820 nm) are commonly used in conjunction with carbon based inks but they are also sensitive to many dye based black inks. Once the scanner wavelength is known, the proper ink can be selected and the PCS of the symbol can be determined.

Also inherent in the design of the optical system is an optical parameter called the depth of field. This parameter can be described in practical terms as the maximum vertical distance at which the wand can be held above the symbol while scanning. When combined with the tip geometry,

this parameter will determine the maximum scan angle for the wand. The depth of field, and resulting scan angle, will define operating characteristics that the operator should become familiar with during training or during the initial implementation of the system. After a short learning period, the operator should become proficient at obtaining successful reads with a wand of a reasonable depth of field and scan angle. There are, however, some situations where the depth of field may be more critical to successful operation. For example, a large depth of field would be required to read through a thick plastic label holder, through a windshield, or over a corrugated surface.

Electrical Characteristics

Bar code wands can be designed to have either an analog or a digital output. Wands with a digital output, such as the Agilent Technologies HEDS-3000/3050 (medium resolution) and HEDS-3200/3250 (high resolution) wands, are generally preferred because they have a consistent, well-specified output. This provides easy installation and easy interchangeability by eliminating the circuit adjustments often necessary with analog wands. A digital output has further advantages to OEM designers as it provides an easy design interface, saves space, and eliminates the design time and hardware costs which would otherwise be required for the digitizing circuit.

A second electrical characteristic important to an OEM designer is supply voltage. This parameter represents another differentiation between analog and digital wands because many analog wands require multiple power supplies while digital wands typically re-

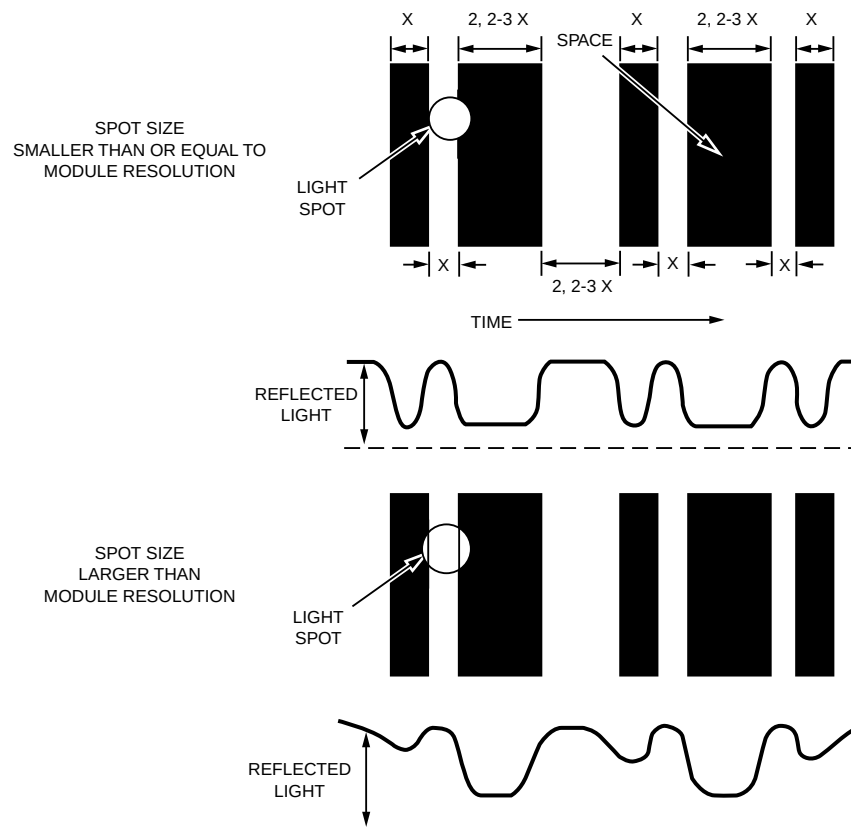


Figure 17. Signal Modulation as a Function of Spot Size vs. Module Resolution

quire a single 5V power supply. Operation from a 5V power supply is an important advantage in designs involving portable terminals and also in stationary terminal designs where the additional power supply voltages would not otherwise be necessary.

Resolution

The minimum element width that can be scanned accurately is commonly referred to as the “resolution” of a wand. Resolution is primarily a function of spot size (or aperture size) and the design of the digitizing circuit. As discussed previously, spot size (or aperture size) will determine how precisely the analog signal replicates the bar/space pattern printed on the symbol (including print errors). The digitizing circuit interprets the analog signal, typically assigning logic 0 values to high signal levels (reflective surfaces/spaces) and logic 1 values to low signal levels (non-reflective surfaces/bars). Assuming constant velocity and adequate PCS, it is the design of this circuit which will determine how accurately the time duration of each logic state represents the width of the corresponding printed bar or space. Note that the integral role of the digitizing circuit makes it impossible to specify resolution for an analog wand.

The resolution capabilities of a digital wand can be specified in terms of error performance at a specific module resolution or in terms of the minimum module resolution that can be represented to some level of accuracy. It is generally preferable to adopt the first alternative, specifying error performance at a specific module resolution, with the module resolution corresponding to one that is popular in the printing of bar code

symbols. Beyond this, it is possible to specify a minimum module resolution which can be scanned with reasonable accuracy.

Agilent Technologies has developed two techniques for measuring digital wand performance. Both techniques describe error performance while scanning a “perfect” test symbol which has a predefined module resolution (narrow bar/ space width). The measurement techniques are described below:

1. Measure width errors produced by the wand when scanning a standard test symbol at constant velocity.
2. Measure the systematic and random components of the width errors produced by the wand when scanning a standard test symbol at a constant velocity. These errors are used in conjunction with a specific algorithm for differentiating between wide and narrow elements to determine the wand's contribution to total system error and, therefore, to the decodability of the symbol. The resulting specification is called the Decodability Index of the wand.

The first technique referred to above measures bar and space width errors. Width error is defined as the difference between the calculated bar (or space) widths and the optically measured bar (or space) widths. When a constant scan velocity is used, width error can be calculated with the following equations:

$$B = t_b \times V_{\text{scan}} \quad S = t_s \times V_{\text{scan}}$$

$$\Delta_b = B - b \quad \Delta_s = S - s$$

where:

B, S = calculated bar (space) width (mm)

b, s = optically measured bar (space) width (mm)

t_b, t_s = wand pulse duration (sec)

V_{scan} = scan velocity (mm/sec)

Δ_b, Δ_s = bar (space) width error (mm)

Width error describes the magnitude of total error that results when a specific module resolution is scanned. The width error technique is utilized in the HEDS-3000/3050 data sheet. Minimum and maximum width errors for both bars and spaces are specified in order to provide information to the software designer regarding the range of error that could be introduced by the wand. These errors, along with printer and operator errors, should be considered in the design of the decoding algorithm.

A more detailed analysis of digital wand errors indicates that wand error consists of both systematic error and random error. The systematic component results from many factors with paper bleed being the primary contributor (see Media section). Thus, systematic error is largely dependent on the media being used. The random component of error results primarily from errors introduced by the digitizing electronics.

Systematic and random errors are more meaningful to the software designer because most systematic errors can be eliminated in the decoding algorithm by separating bars and spaces. A further step can be taken, however, which evaluates these errors in conjunction with a specific threshold setting and decision algorithm and specifies the wand's contribu-

tion to system error. This specification, called the Decodability Index for the wand, can be combined with the decodability index of the printer, and other system elements, to determine the decodability index of the entire system. This can then be compared to the Decodability Limit of the symbology being scanned. A bar code symbol will be decodable even with worstcase accumulated errors if the combined decodability index is less than the decodability limit.

The following section presents a derivation of the concept of decodability. System errors, a threshold setting and decision algorithm, and the interrelationship of the two will be discussed.

Decodability

The digital signal output of a wand scanning at a constant velocity will present width information to the decoder which includes the nominal widths of the bars and spaces (elements) plus both systematic and random error components. This can be illustrated, in general, by the following equation:

$$E' = E + OS \pm \delta_e \quad (1)$$

where:

E' = calculated element width at wand output

E = nominal printed element width

OS = systematic error or "offset"

δ_e = random error

An algorithm designed to differentiate between the wide and narrow elements of a two-level bar code symbol establishes a threshold, compares the actual

width information to that threshold, and then decides whether the element is wide or narrow. A simple threshold-setting technique finds the mid point between wide and narrow elements as shown below:

$$T = \frac{W + N}{2}$$

where:

T = threshold

W = wide element width

N = narrow element width

In practice, the threshold-setting technique has to function in the presence of system errors which cause the wide and narrow element widths to vary from their nominal values. The threshold varies depending on which elements are chosen to set it. A low threshold may cause a narrow element with large positive errors to appear as a wide element. The lowest, worst-case threshold will occur when the wide and narrow elements selected are the narrowest ones in the character being decoded. The minimum threshold is defined by the equation:

$$T_{\min} = \frac{W(\min) + N(\min)}{2} \quad (3)$$

where:

$T_{\min}$ = minimum threshold

$W(\min)$ = narrowest wide element
= $W + OS_w - \delta_{eW}$

$N(\min)$ = narrowest narrow element
= $N + OS_N - \delta_{eN}$

In order for the decoding algorithm to correctly identify wide and narrow elements, the widest narrow element must be less than the minimum threshold. Therefore,

$$N(\max) < T_{\min} \quad (4)$$

where:

$N(\max)$ = widest narrow element
= $N + OS_N + \delta_{eN}$

Now, by substituting equation (3) into equation (4), by using the definitions of $W(\min)$, $N(\min)$, and $N(\max)$, by assuming $\delta_{eW} = \delta_{eN} = de$, and by performing some algebraic manipulations, the inequality can be transformed to:

$$\frac{W - N}{4} > \frac{OS_N - OS_W}{4} + de \quad (5)$$

Equation (5) can then be normalized by a narrow element (N) so that:

$$\frac{W/N - 1}{4} > \frac{OS_N - OS_W}{4N} + \frac{de}{N} \quad (6)$$

Note that W/N is the wide-to-narrow ratio defined by the bar code symbology and is therefore a constant. The term $(W/N - 1)/4$ is defined as the Decodability Limit. The right side of the inequality contains all of the error terms and can be defined as the Decodability Index. The resulting equations are listed below with the values for decodability limit and decodability index being expressed as percentages.

$$DL > DI \quad (7)$$

where:

$$DL \triangleq \frac{W/N - 1}{4} \times 100\% \quad (8)$$

and

$$DI \triangleq \frac{OS_N - OS_W}{4} + \frac{de}{N} \times 100\% \quad (9)$$

There are several interesting observations that result from this derivation:

- A larger W/N ratio for the symbol increases the decodability limit. This allows a greater margin for system errors and should increase the read rate.
- DL is a constant whose value is determined by the $W:N$ ratio of

the symbology. DI, on the other hand, is a function of both system errors and the nominal narrow element width, N. Thus, if the magnitude of error remains constant and the element widths are increased, the value of DI will decrease. This, in turn, should improve the read rate.

- Systematic errors or “offsets” contribute to system error only if there is a difference in offset between wide and narrow elements. (Note: There is typically a small difference in offset between wide and narrow bars or wide and narrow spaces. However, a significant difference in offset generally exists between bars and spaces. It is, therefore, preferable to separate bars and spaces in the decoding algorithm. This separation was assumed at the beginning of the derivation).
- Random errors contribute directly to system error.

Once the general concept is understood, the decodability index for the system can be obtained from the system elements that contribute to error. Since the printer and wand are the primary sources of error, this can be summarized as follows:

$$DI_{\text{system}} = DI_{\text{printer}} + DI_{\text{wand}} \quad (10)$$

Equation (10) can be substituted into equation (7) with the resulting inequality being defined independently for bars and spaces as shown below:

$$DL_b > DI_{bp} + DI_{bw} \quad (11)$$

$$DL_s > DI_{sp} + DI_{sw} \quad (12)$$

A detailed breakdown of equations (11) and (12) yields the

error sensitivity equations stated in the HEDS-32XX data sheet and also presented below:

Space Error Sensitivity

Decodability Limit (DL_s) > Printer (DI_{sp}) + Wand (DI_{sw})

$$\frac{(WS: NS - 1)}{4} > \frac{(OS_{spN} - OS_{spW}) + (3\delta_{spN} + \delta_{spW})}{4m} + \frac{(OS_{swN} - OS_{swW}) + 4de_{sw}}{4m} \quad (13)$$

Bar Error Sensitivity

Decodability Limit (DL_b) > Printer (DI_{bp}) + Wand (DI_{bw})

$$\frac{(WB:NB - 1)}{4} > \frac{(OS_{bpN} - OS_{bpW}) + (3\delta_{bpN} + \delta_{bpW})}{4m} + \frac{(OS_{bwN} - OS_{bwW}) + 4de_{bw}}{4m} \quad (14)$$

where:

Bars	Spaces	Definition
DL_b	DL_s	Decodability Limit
DI_{bp}	DI_{sp}	Printer decodability index
DI_{bw}	DI_{sw}	Wand decodability index
$WB:NB$	$WS:NS$	Wide to narrow ratio
OS_{bpN}	OS_{spN}	Printer offset, narrow element
OS_{bpW}	OS_{spW}	Printer offset, wide element
OS_{bwN}	OS_{swN}	Wand offset, narrow element
OS_{bwW}	OS_{swW}	Wand offset, wide element
δ_{bpN}	δ_{spN}	Printer random error, narrow element
δ_{bpW}	δ_{spW}	Printer random error, wide element
de_{bw}	de_{sw}	Wand random error
m	m	Module width (narrow element width)

Note that the random errors for the printer are not assumed equal for wide and narrow elements. This is done because the printer random errors are, in practice, not equal, whereas wand random errors are approximately equal.

In order to make use of equations (13) and (14), the system designer

must know the values for the expressions stated in the equations. This information can be obtained from the vendor's data sheet or can be determined through a series of measurements. Hewlett-Packard specifies the decodability index (DI_w) for the HEDS-32XX wands on their data sheet.

The DI_w stated represents the decodability index for bars because bars typically have a larger decodability index than spaces and, therefore, the specification is more conservative. For example, the typical DI_w stated in the data sheet (for bars) is 14%, whereas the typical DI_w for spaces is actually 8%.

In summary, a bar code symbol will be decodable if the accumulated system errors yield a system decodability index which is less than the decodability limit of the symbology. Note that this conclusion is based on the assumptions that errors are additive and that the lowest, worst-case threshold is used by the decoding algorithm. If these conditions do not exist, then a symbol with $DI > DL$ may still be decodable. Additionally, some more advanced decoding techniques can effectively increase the value of DL , thus allowing a symbol with a higher DI to be decoded. The concept is, nonetheless, a good analytical tool for evaluating system errors.

The material on decoding algorithms presented in this section only covers a portion of the total software package which must be developed in order to read bar codes. The following section discusses the design of a decoder at greater length and also presents some operational considerations in the selection of bar code reading equipment.

Bar Code Readers

A bar code decoder acts as a data interpreter or translator of the serial time data provided by the wand. It converts this serial data into ASCII data, or other binary coded data, which is then formatted into a specific communication protocol for transmission to the

host computer. The bar code reader which houses the decoder generally includes a scanner and also performs other functions or has other features in addition to decoding and data transmission. These functions or features may include any, or all, of the following:

1. Audio operator feedback (beeper)
2. Visual operator feedback (indicator(s), single line display, or CRT display)
3. Alternate data entry technique (keyboard, magnetic stripe, or punch card).
4. User programming of feedback, data formatting, and terminal functions.

The selection criteria for bar code readers should be tailored to the application. First read rate and substitution error rate must be considered in addition to the data communication protocol and the functions/features listed above. The performance of the decoder in terms of first read rate and substitution error rate should be evaluated under real-life conditions, not in a lab environment. This is necessary because these parameters will vary with the symbology, media, print quality, print contrast, operator, and operating environment, as well as the reader characteristics (scanner/decoder combination). Only a real-life test can demonstrate the performance realized by the entire system.

The functions or features desired in an application will depend on the level of interaction required between the operator and computer, the amount of system control or programmability required, and the number of data entry techniques used for inputting data to the computer. The

minimum requirement for a bar code reader is usually an audio beeper actuated by the decoder which will signal a good read to the operator. This capability is provided by Agilent Technologies' 16801A Bar Code Reader. More and more applications are moving toward a higher level of computer-operator interaction where, for example, the computer would command audio or visual feedback to the operator. This feedback could signal the receipt of valid data, provide instructions to the operator, or perform some other pre-defined function. Agilent Technologies' 16800A Programmable Bar Code Reader offers programmable operator feedback as one of many programmable features designed to facilitate sophisticated bar code data entry systems. Some applications require multiple data entry techniques, including bar code, magnetic stripe, punch card, and/or keyboard. Multifunction terminals such as Agilent Technologies' 3075A Data Collection Terminal can be used in these applications.

As the evolution toward systems using only bar code data entry continues, more and more applications will require less expensive bar code readers which do not have multiple data entry capabilities. Where a "back-up" is required to provide an alternate method of entering data on non-readable symbols, pre-printed bar code menus can be used. These menus contain a numeric (or alphanumeric) character set in bar code as well as bar-coded control functions which signal the computer that manual data entry is to begin, or has ended. In addition, the menus can be designed to include special symbols which signify the completion of a step or the condition of an item.

There are many aspects of decoder design which will influence the decoder's contribution to system performance. Software functions that the processor should provide are listed below:

1. Margin/start (or stop) character recognition
2. Bar/space width measurement
3. Algorithms for wide/narrow threshold setting
4. Identification of character bit image (one/zero decode)
5. Character error checking
6. Message error checking (if selected)
7. Stop sequence recognition
8. ASCII character formation

The implementation of these functions will vary depending on the symbology involved. As with any system, the software design will have a significant impact on performance. As mentioned previously, the software should be tolerant of system errors to provide a high first read rate but should not sacrifice data accuracy in the process. The fundamentals of decoder design are discussed at length in Application Note 1014. The concepts presented in Application Note 1014 are implemented in Agilent Technologies' HEDS-0100/0150 Decoder Module for 3 of 9 code.

Conclusion

A bar code system is comprised of six major interactive elements: symbology, media, printer, operator, scanner, and decoder. Successful implementation of a bar code system requires a thorough understanding of the interaction of the system elements and careful consideration in the selection of the system elements. A well designed system is characterized by a high first read rate, a low substitution error rate, and

little downtime.

The symbology selected must have a character set consistent with the data to be encoded and must also have an information density capability consistent with the space limitations of the application. There are several general observations regarding the selection of the symbology:

1. Medium/low resolution module widths will widen the spectrum of printers to choose from, including some lower cost, more flexible types.
2. The wide element to narrow element ratio should be selected after considering the information density needs of the system and the effect of this parameter on the decodability limit. A larger ratio (3:1) will result in lower information density and a higher Decodability Limit (DL). In general, a 2.2:1 ratio is used for high module resolutions, a 2.5:1-3:1 ratio is used for medium module resolutions, and a 2:1-3:1 ratio is used for low module resolutions.
3. Self-checking codes do not require the use of a checksum character to achieve good data accuracy. However, a checksum character is recommended where data accuracy is extremely important.
4. Code selection should include the consideration of future system expansion and the incorporation of new application areas. An alphanumeric code may be preferred even if the existing requirements are for numeric data.
5. The 3 of 9 code is the most common alphanumeric code. Interleaved 2 of 5 code is a popular numeric code with very high information density capa-

bilities, but is difficult to print on-demand in high resolution due to its continuous structure. Matrix 2 of 5 code and Code 11 are two discrete numeric codes with high information densities.

The media selected to support the symbol should be an opaque material with high reflectivity, a diffuse radiation pattern, and good durability. Heavyweight white paper stock with a high rag content and smooth surface texture is recommended for clean environments where a limited number of scans are anticipated. A clear protective covering with a thickness less than 0.25 mm (0.01 in.) should be used in dirty environments and in applications where a symbol will be scanned many times. Vinyl, polyester, and other special media may be preferred for some particularly hostile environments. Specular surfaces should be avoided as they can degrade scanner performance.

High print quality and adequate print contrast are essential to the success of the system. Thus, the selection of the printer and ink, or the source of pre-printed labels, is extremely important. Symbols with clearly printed, uniform bars, and well-toleranced wide to narrow bar/space ratios should be readable if the PCS is maintained greater than 70%. Since PCS is wavelength dependent, it should be evaluated at the wavelength of the scanner's emitter. As a general rule, visible red emitters (633 nm, 700 nm) and near infrared/infrared emitters (820 nm, 930 nm) can be grouped together for this evaluation.

The criteria used to select a printer, or a source of preprinted labels, should include the volume of labels or forms, the information

flow which defines the message to be encoded, and cost trade-offs. When pre-printing is feasible and high volumes of symbols are required, there are two basic choices: commercial printing and on-site printing with computer controlled page printers such as the Hewlett-Packard 2680 laser printer. If high resolution symbols are to be printed, then a commercial process is preferred. For moderate volume preprinting or on-demand printing, "drummer" formed character printers or dot matrix printers, such as the Hewlett-Packard Factory Data Printer, may be used. The "drummer" printers are the only choice for high resolution labels because dot matrix printers are not capable of high resolutions. For medium and low resolution symbols, dot matrix printers may be preferred because of their lower cost and greater flexibility. If the application is small and a low volume of symbols is required, then it may be more practical to obtain pre-printed labels from a printer supplier who provides a label service.

Once the symbology has been selected and the symbols have been printed, the operator, scanner, and decoder must work together to read the symbol. The selection of the scanner and the reader which houses the decoder should be based on first read rate, substitution error rate, operator feedback provided, programmability, reliability, and environmental compatibility. Since operators cannot always be selected, they should be trained on the operation of the scanner used in the system.

First read rates and substitution error rates should be evaluated under actual-use conditions. First read rates under real-life condi-

tions should be greater than 80%, assuming reasonably well-printed symbols and trained operators. Substitution error rates can be minimized by using self checking bar code symbologies and checksum characters. Industry experience with the 3 of 9 code indicates that substitution error rates better than one error in a million characters are achievable, even without the use of a checksum character. The actual substitution error rate for the system may be evaluated through prototype or test site installations or may, alternately, be evaluated later based on accumulated experience with the system. Whatever the result, the error rates for a bar code system should show a dramatic improvement over those experienced using punch cards, keyboards, or OCR characters for data entry.

Operator feedback and programmability are bar code reader features which determine the amount of computer-operator interaction possible in the system. A reader with simple audio or LED feedback may be acceptable for some applications. If the reader is programmable and can be daisy-chained with a CRT display, as is the Agilent Technologies 16800A Programmable Bar Code Reader, then the interaction capabilities are virtually endless. Keyboards may, or may not, also be desired depending on how much flexibility the operator is to be given in entering data. The training required to use a keyboard and the errors inherent in their operation should be considered before they are implemented.

The reliability and environmental compatibility of the scanner and reader should also be considered when selecting equipment. Once

again, testing under real-life conditions should prove extremely valuable in differentiating between actual reliability/compatibility and apparent reliability/compatibility.

The final consideration in the selection of bar code equipment is system downtime. A well designed data entry system is clearly of little use if it is not functional. System downtime can be minimized by taking several steps:

1. Select reliable equipment, including the host computer system.
2. Conduct frequent checks on the printer to ensure that easily readable symbols are being printed. Perform maintenance as necessary to maintain high print quality.
3. Select vendors who can provide local repair service in case of equipment failure.
4. Select vendors who are knowledgeable of, and have responsibility for the complete system including the computer equipment and application software.
5. Inventory a small stock of spare equipment.

It is, or should be, apparent that the design and implementation of a bar code system requires careful planning. A test site installation is recommended to evaluate the performance of the bar code equipment and the application software. A well-designed system can offer many rewards to the user including improved productivity, reduced inventory levels, improved material flows, and improved traceability/accountability.

As a manufacturer of computers, bar code printers, bar code readers, and scanners, Agilent

Technologies is well equipped to support your needs for bar code equipment and complete factory data collection systems. Please contact us for more information.

Glossary Of Terms

Bar – the darker, non-reflective, element of a bar code.

Bar Code – a predetermined pattern of bars and spaces which represents numeric or alphanumeric information in machine readable form.

Bar Code Symbol – a complete message encoded in bar code for entry into a computer. A bar code symbol consists of a start margin, start character, data or message characters, checksum character (if any), stop character, and stop margin.

Bi-Directional Symbol – a bar code symbol format which permits reading in complementary (opposite) directions across the bars and spaces.

Character – a letter, digit, or special symbol which is used as a part of the representation, organization, or control of data.

Checksum Character – a calculated character included within a message for error detection. (Note: may also be referred to as a check digit)

Continuous Code – a bar code which does not have inter-character spaces as part of its structure.

Decoder – the part of a bar code reader which accepts the serial time data provided by the wand and translates it into computer readable ASCII data, or other binary coded data.

Decodability Index – a quantitative measure of cumulative errors contributed by all elements of the bar code system or of one of the system elements (printer, wand, etc.). It is expressed as a percentage of the narrow bar/space width.

Decodability Limit – the maximum Decodability Index which can be allowed by the system design while still ensuring that the bar code symbol will be decodable. The Decodability Limit is a function of the wide-to-narrow ratio used to create the symbol.

Depth of Field – the distance between the minimum and maximum plane in which a bar code symbol can be read.

Discrete Code – a bar code which contains an intercharacter gap as part of its structure. Each character is, consequently, independent of other characters in the symbol.

Edge Roughness – edge irregularities with respect to a nominal bar edge.

Element – a generic term used to refer to either a bar or space.

First Read Rate – the percentage of correct readings that will be obtained in one pass of the scanner over the symbol.

Fixed Beam Scanner – a stationary bar code scanner which uses a fixed (or stationary) beam of light to read bar code symbols. The symbol must be moved through the light beam to be read.

Four-level Code – a bar code which uses four different element widths in its structure.

Hand-Held Scanner – A scanner held and operated by a human operator, thus enabling the scanner to be brought to the symbol.

Information Density – the number of data or message characters which can be represented per unit length of space. "Theoretical" information density is calculated assuming an infinitely long symbol so that the start and stop characters will not effect its value. "Actual" information density is calculated for a finite symbol length.

Intercharacter Space – the

space between message characters in discrete bar codes.

Interelement Spaces – the spaces between bars in bar codes which use only bars to encode binary data.

Margin – an area before the start character and after the stop character which is devoid of printed material. (Note: may also be referred to as quiet zones)

Media – the underlying surface on which the bar code is printed. (Note: may also be referred to as the substrate)

Message – the string of data characters encoded in a bar code symbol, excluding the checksum character.

Message Length – the number of data characters contained in a single encoded message.

Mis-read – a message which is decoded incorrectly and transmitted to the host computer. The transmitted data does not agree with the encoded data.

Module – the narrowest element (bar or space) in a bar code.

Module Resolution – the width of the modules, or narrowest elements, of a bar code symbol.

Module Width Encoding – a method of bar code encoding where narrow elements represent binary zeros and wide elements represent binary ones.

Moving Beam Scanner – a stationary bar code scanner which uses a moving light beam to dynamically scan a bar code symbol.

No-Read – a scan attempt which does not result in a successfully decoded symbol.

Non-Return-to-Zero (NRZ) Encoding – a method of bar code encoding where binary zeros and ones are represented by reflective and non-reflective modules, respectively. A series of four binary zeros is, for example, represented by a non-reflective area four modules in width.

Paper Bleed – an optical phenomenon which causes bars to appear larger, and the spaces narrower, than they are actually printed. It is caused by the scattering of incident light rays within the media.

Print Contrast Signal – a mathematical expression of the relationship between the reflectivity of the bars (R_b) and the spaces (R_w):

$$PCS = \frac{R_w - R_b}{R_w} \times 100\%$$

R_b (Black Reflectance) – the reflectivity of the bars at the wavelength of the scanner.

R_w (White Reflectance) – the reflectivity of the spaces at the wavelength of the scanner.

Radiation Pattern – the optical pattern of light that leaves the media surface, as described by the radiated light intensity at various angles.

Random Errors – errors introduced by the printer, wand, operator, or other system elements which are random. Because they are random, those errors encountered during one scan may not be encountered during the next scan.

Reader – a device used for reading bar codes. A reader typically consists of a scanner, decoder, and data communication interface.

Reflectivity – the amount of incident light which is reflected back to the scanner's detector, expressed as a percentage of the total incident light.

Resolution – the minimum element width that can be accurately scanned by a scanner consisting of an optical system and digitizing circuit. (Note: the module resolution of the symbol is sometimes referred to the symbol's resolution, thus adding a second possible meaning for

this term).

Scanner – an optical and electronic device that scans bar code symbols and outputs serial time data which corresponds to the widths of the bars and spaces.

Space – the lighter, reflective, element of a bar code.

Specks – dark areas in the spaces of a bar code symbol which are caused by printing errors, dirt, or wear.

Specular – a term describing a surface with mirror-like reflecting properties.

Spot Size – the size of the focused image of the emitter as it appears on a surface at the focal point of the optical system. (Note: aperture size is an equivalent term for scanners which use a focused detector image)

Start Character – a special pattern of bars and spaces used to identify the beginning of a bar code symbol.

Stationary Scanner – a scanner that is permanently mounted and which reads bar code symbols passed through its field of view.

Stop Character – a special pattern of bars and spaces used to identify the end of a bar code symbol.

Substitution Error Rate – the ratio of the number of invalid, or incorrect characters entered into the data base to the number of valid characters entered.

Systematic Error – errors introduced by the printer, wand or other system elements which are consistent for all bars and/or all spaces.

Two-level Code – a bar code which uses two element widths, wide and narrow, in its structure.

Voids – light areas in the bars of a bar code symbol which are usually caused by printing errors.

WB:NB – the wide bar to narrow bar ratio for a bar code which encodes binary information in bars.

WE:NE – the wide element to narrow element ratio for a bar code which encodes binary information in both bars and spaces.

Wavelength – a term describing the frequency of light radiated by the scanner's emitter.

Wide-to-Narrow Ratio – the ratio between the width of the wide elements and narrow elements in a two level bar code.

Width Error – the difference between the bar (space) widths calculated from the scanner's digital output and the optically measured bar (space) widths.

Bar Code Standardization References

Reference	Standard
American Blood Commission 1901 North Fort Myer Drive Suite 300 Arlington, VA 22209	Committee for Commonality in Blood Banking Automation Final Report 1977 Volume III, ABC Symbol • Codabar
American National Standards Institute (ANSI) 1430 Broadway New York, NY	Specifications for Bar Code Symbols on Transport Packages and Unit Loads (ANSI MH10.8-1983) • 3 of 9 Code • Interleaved 2 of 5 Code • Codabar
Automotive Industry Action Group (AIAG) 466 Stephenson Hwy. Troy, MI 48084	Bar Coding Specifications by Automotive Industries Action Group (proposed) • 3 of 9 Code • Interleaved 2 of 5 Code
Department of Defense (LOGMARS) Director, DARCOM Packaging, Storage and Containerization Center- Attention: SDSTO-TP Tobyhanna, PA 18466	MIL-STD-1189 • 3 of 9 Code
Distribution Symbol Study Group (DSSG) Specifications are available from AIM or: The Fiber Box Association 5725 East River Road Chicago, IL 60631	Recommended Practices for Uniform Container Symbol/UCS Transport Container Symbol/TCS • USD-1 • USD-2
Material Handling Institute/ Automatic Identification Manufacturers Product Section (MHI/AIM) 1326 Freeport Road Pittsburgh, PA 15238	Uniform Symbol Descriptions (USD) • USD-1 (Interleaved 2 of 5 Code) • USD-2 (3 of 9 Code Subset) • USD-3 (3 of 9 Code) • USD-4 (Codabar)
Uniform Product Code Council, Inc. 7051 Corporate Way, Suite 201 Dayton, Ohio 45459	UPC Shipping Container Symbol Specification • Interleaved 2 of 5 Code

