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[54] METHOD AND APPARATUS FOR DECODING TWO-DIMENSIONAL BAR CODE USING CCD/CMD CAMERA

3903595 8/1990 Fed. Rep. of Germany 235/462

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[21] Appl. No.: 851,493

[22] Filed: Mar. 16, 1992

[57] ABSTRACT

[51] Int. Cl.⁵ G06K 7/10; G06K 9/00

[52] U.S. Cl. 235/462

[58] Field of Search 235/462, 470, 471

A method and apparatus for decoding a two-dimensional bar code symbol using a charge-coupled device (CCD) camera or a charge-modulation device (CMD) camera. The CCD/CMD camera takes pictures of the symbol and the picture is converted into digital data. The location and orientation of the two-dimensional bar code symbol is determined and verified. Defects and damages on the symbol are detected and corrected. The symbol is scanned to read the codewords of the two-dimensional bar code symbol.

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46 Claims, 12 Drawing Sheets

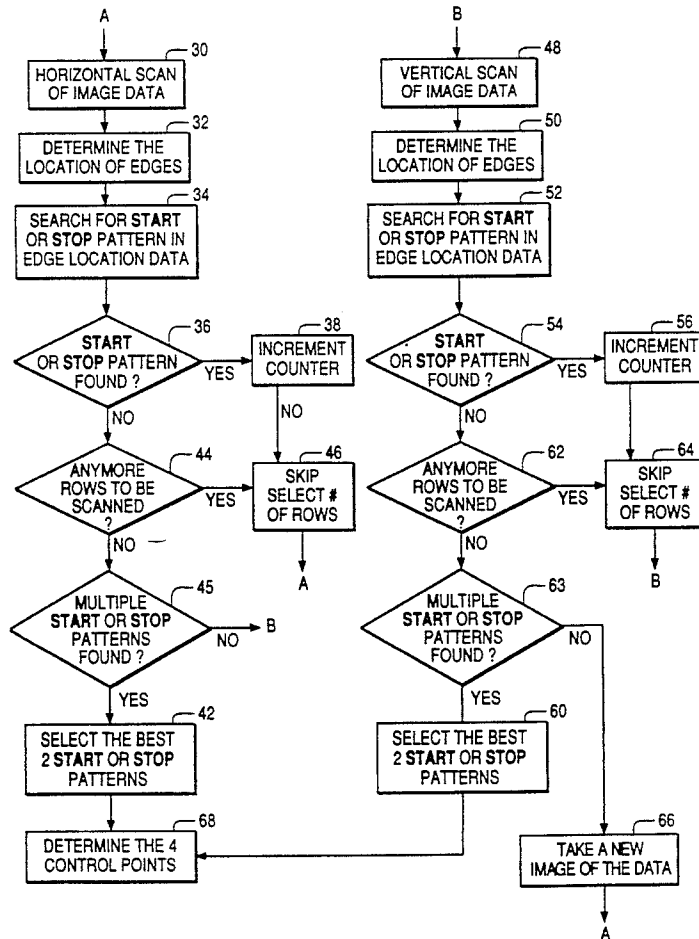


FIG. 1

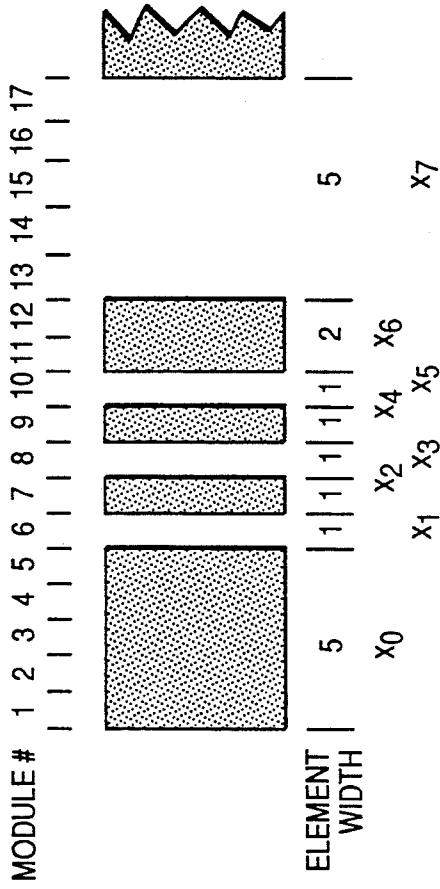


FIG. 2

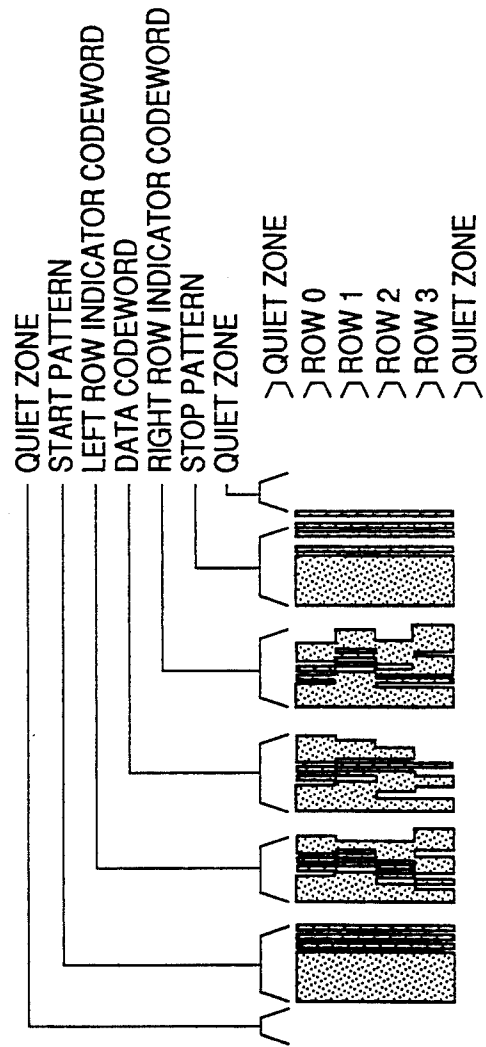


FIG. 3

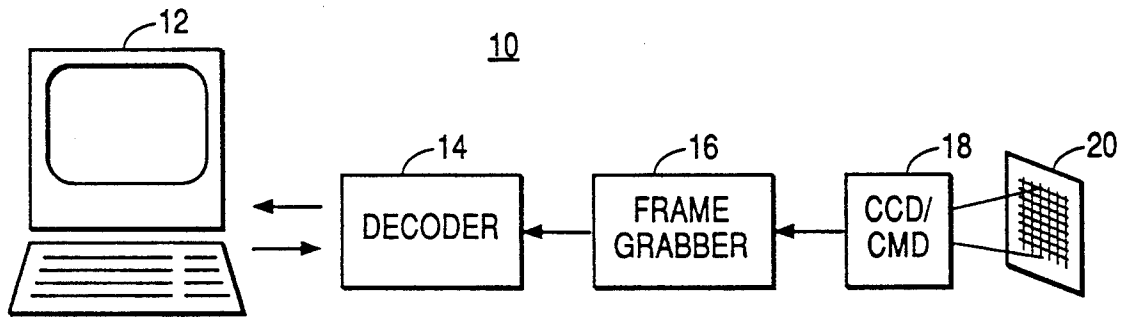


FIG. 4

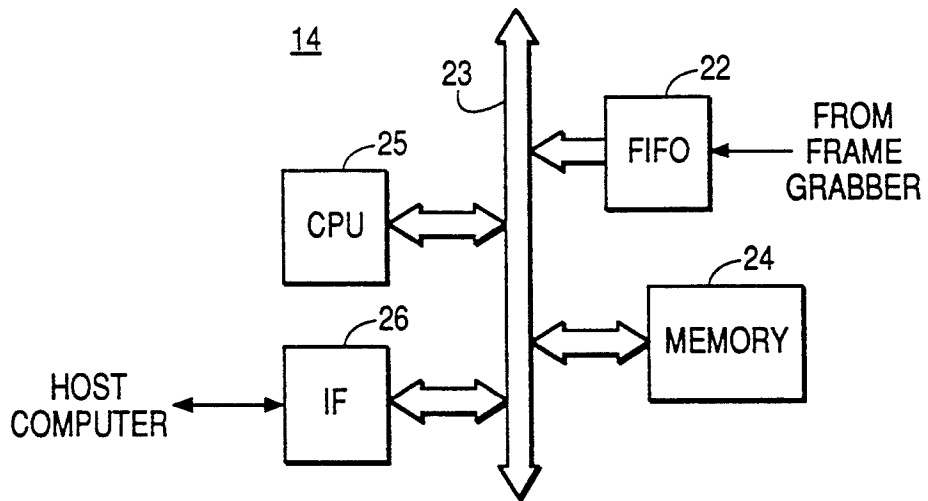


FIG. 5

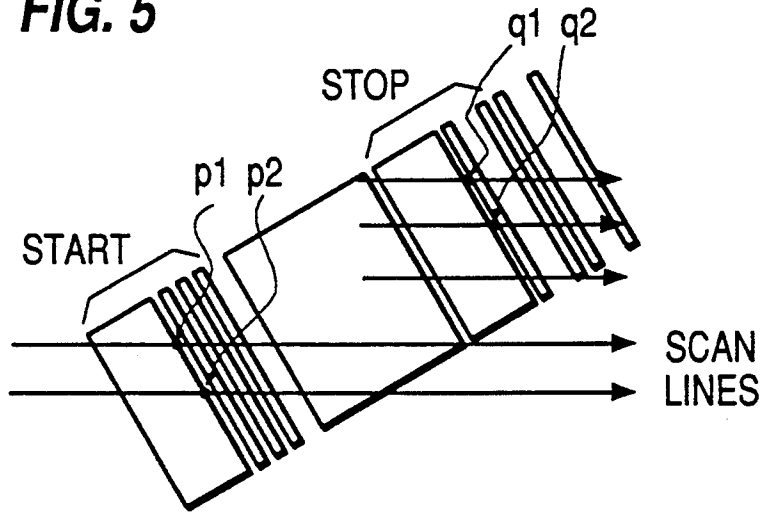


FIG. 6

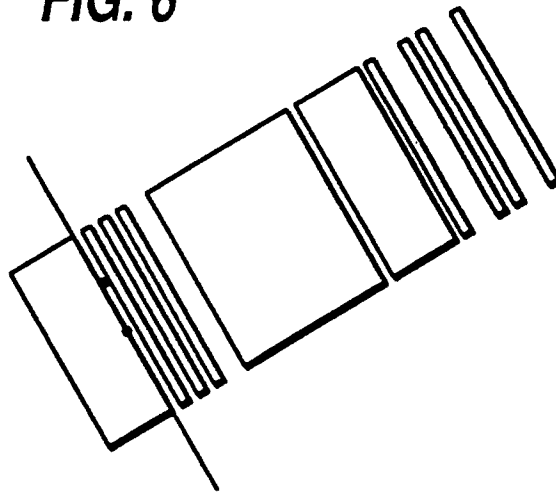


FIG. 7

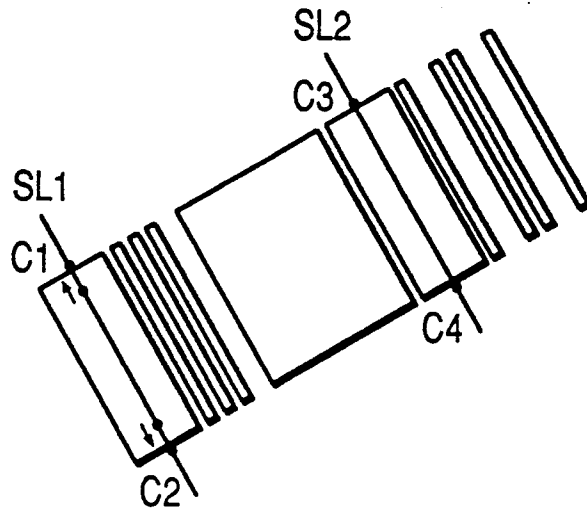


FIG. 9

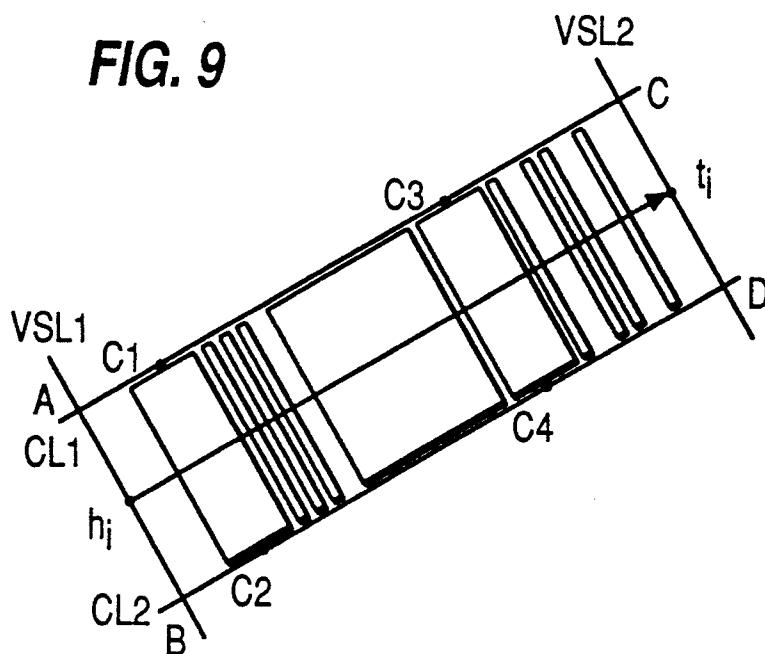


FIG. 8A

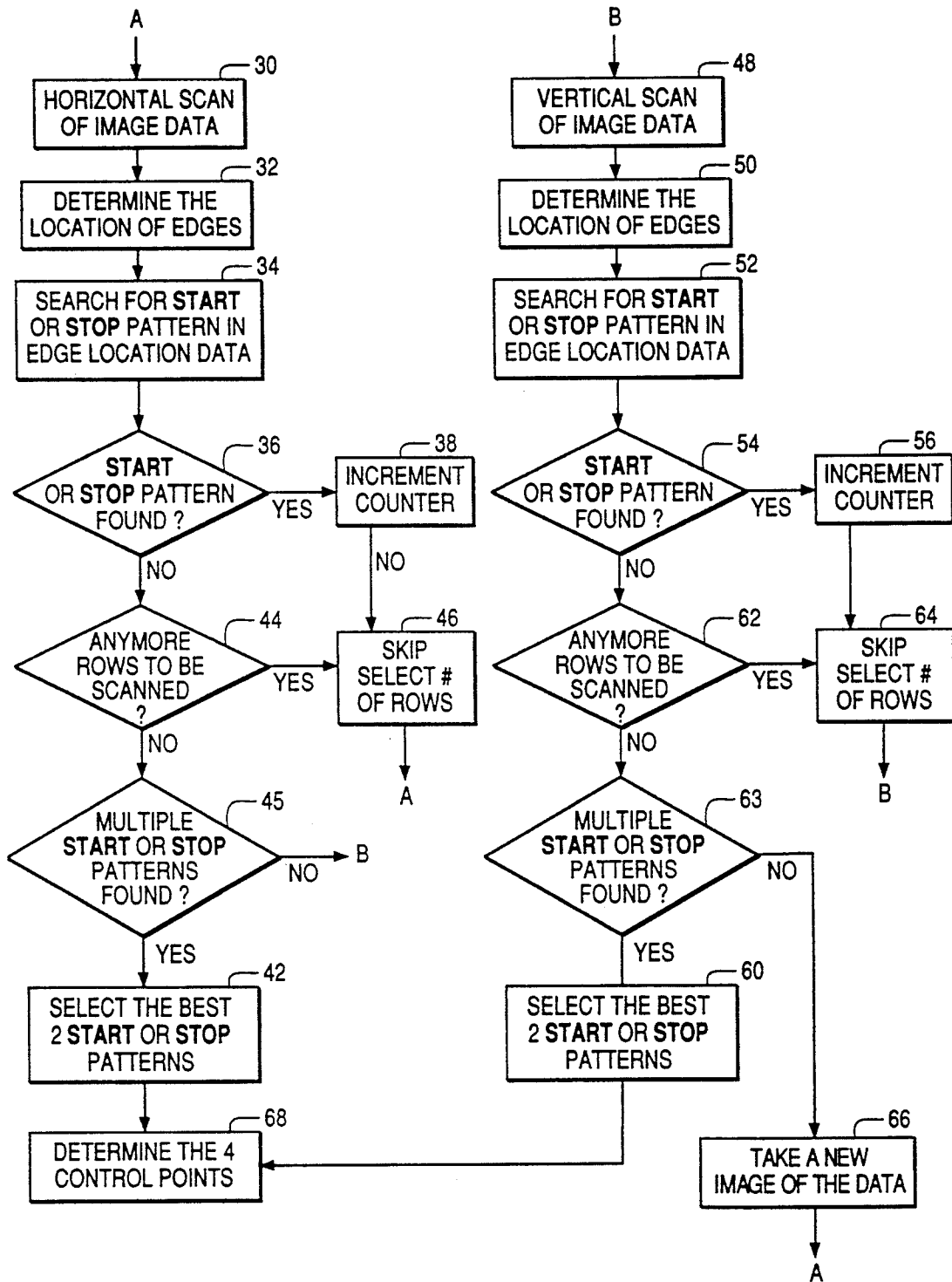


FIG. 8B

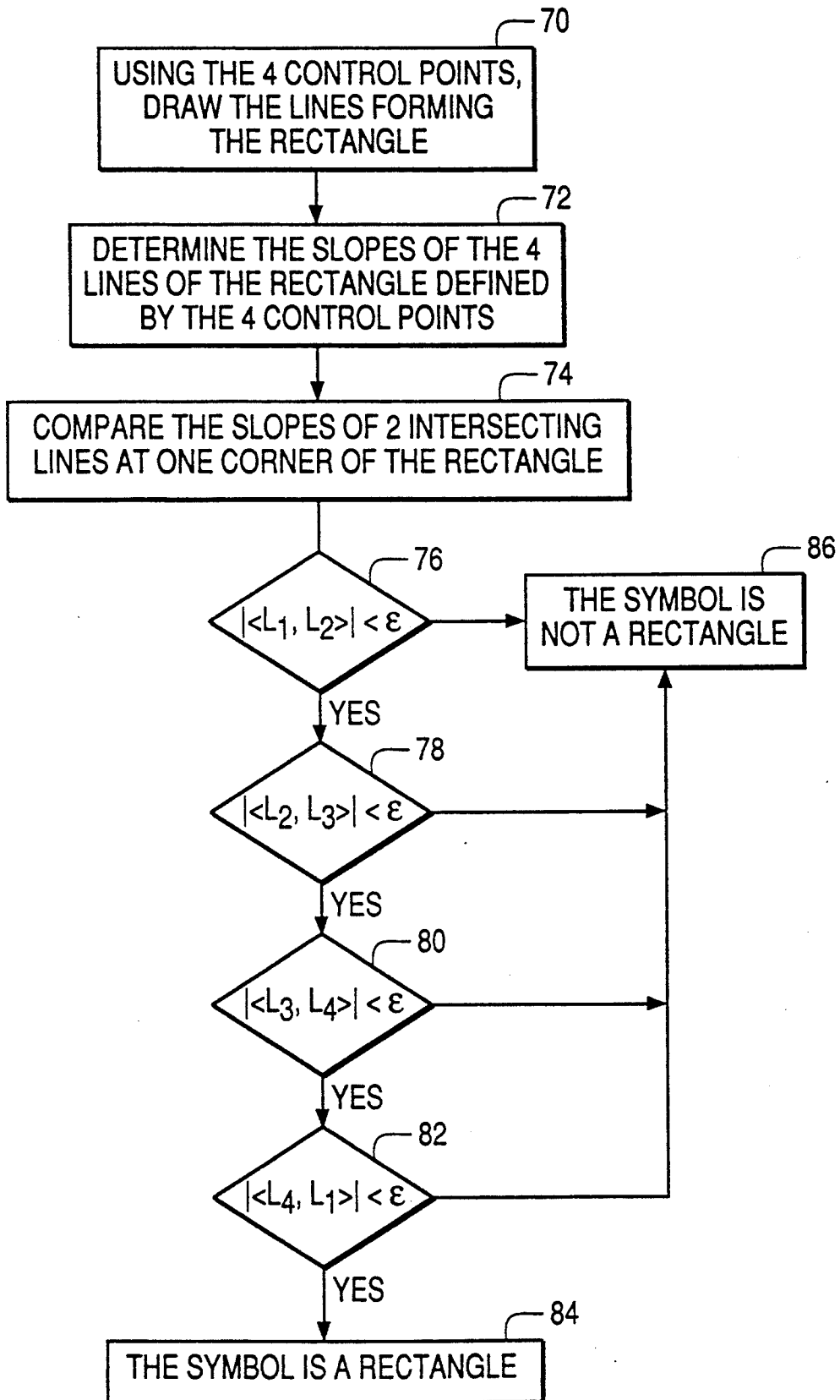


FIG. 10

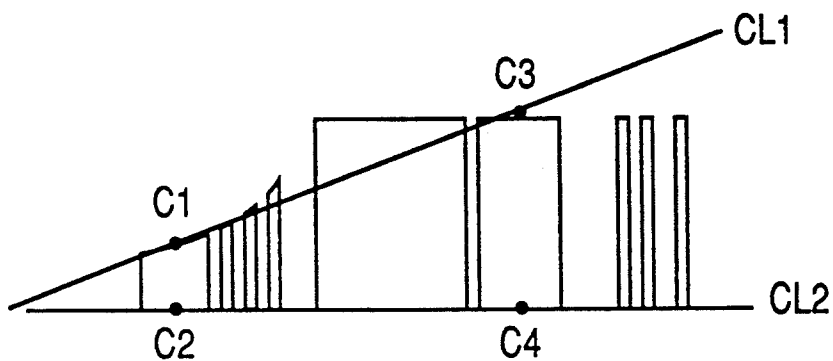


FIG. 11

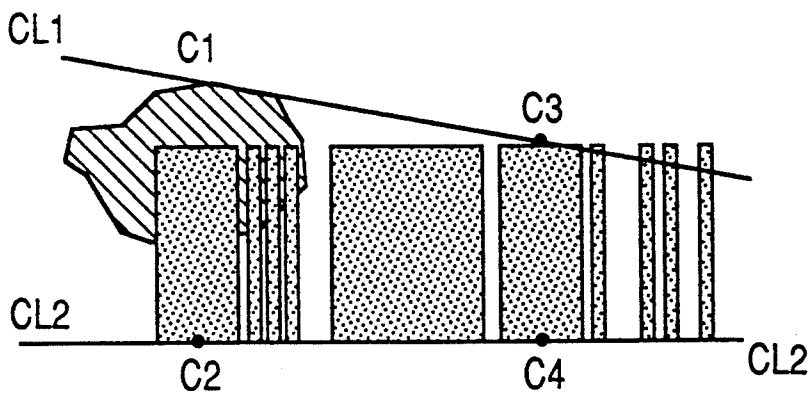


FIG. 12

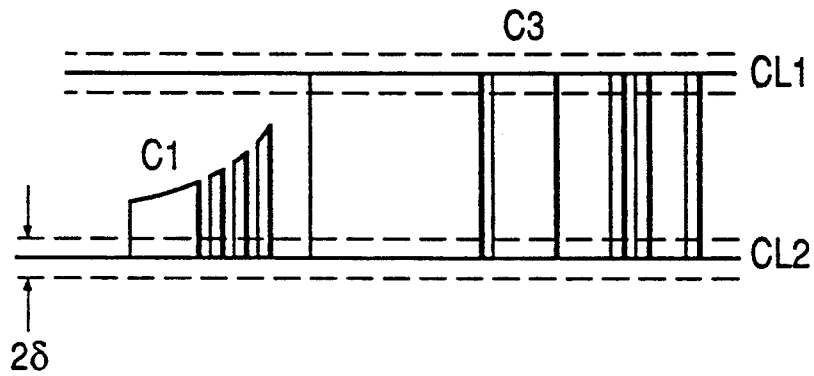


FIG. 14

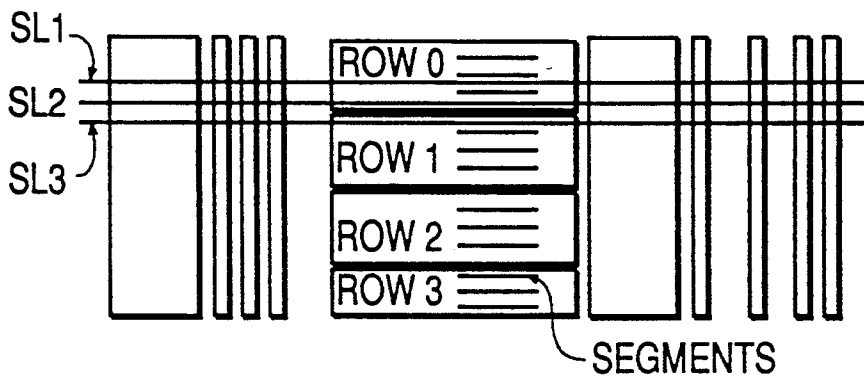


FIG. 13

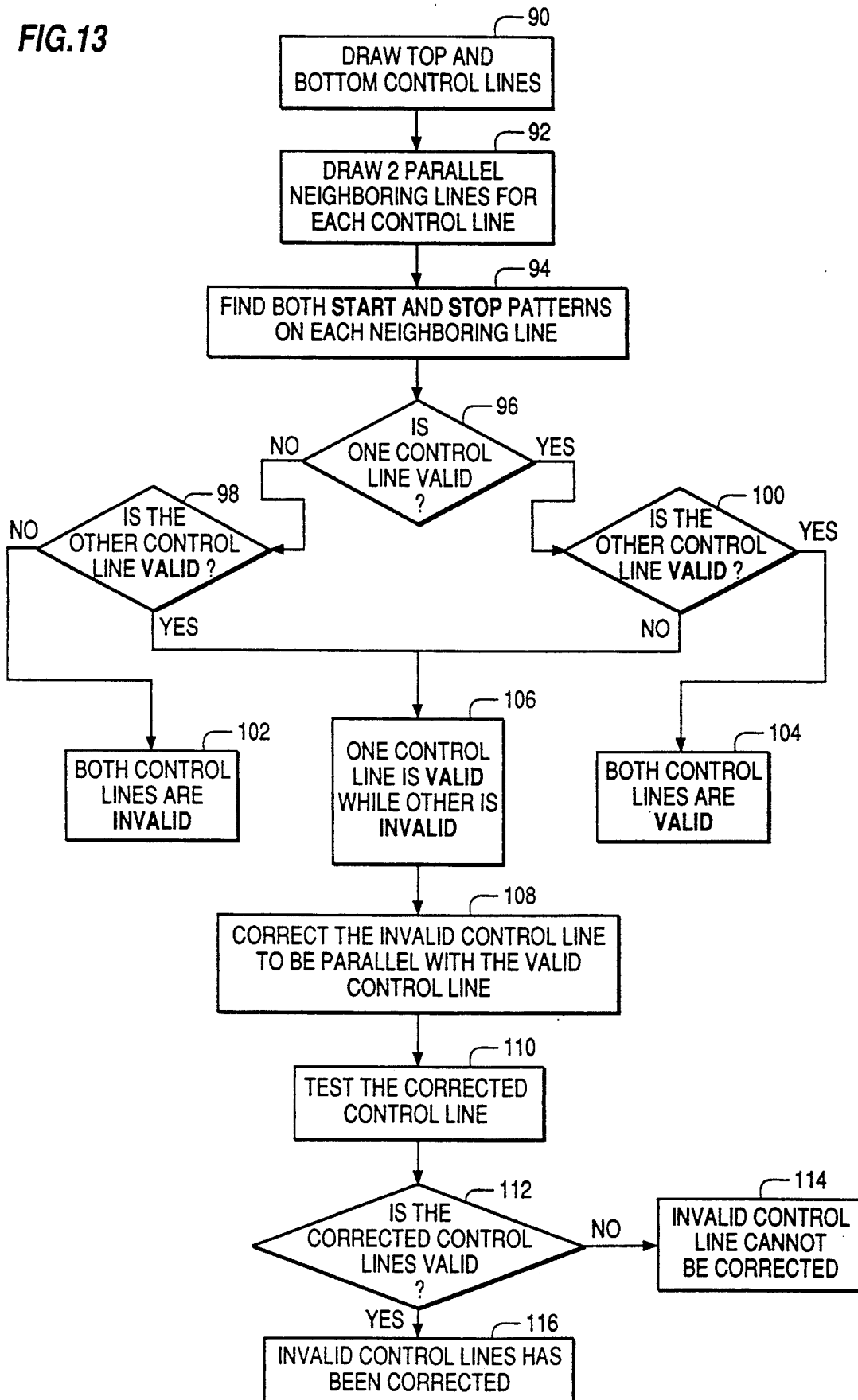


FIG.15A

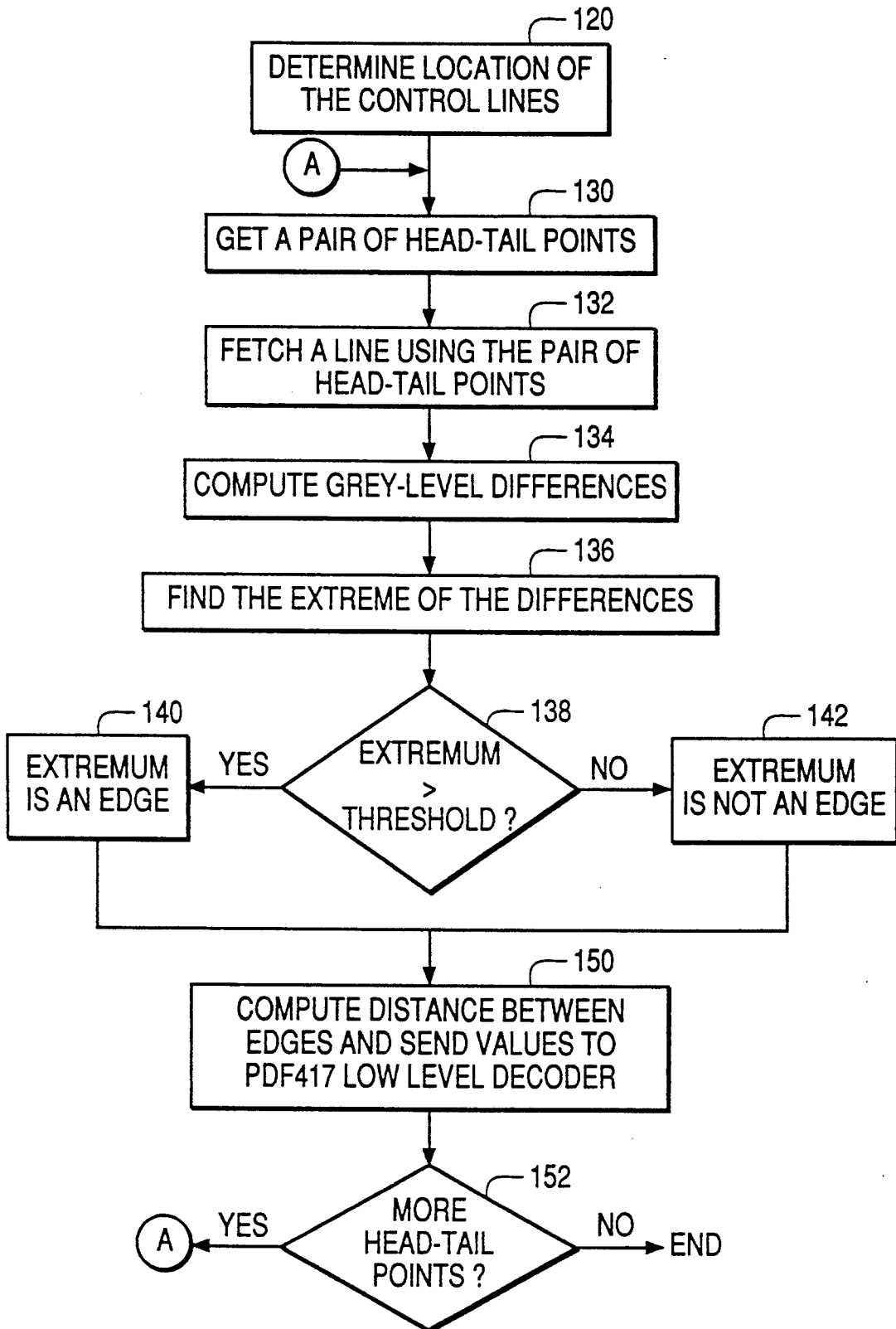


FIG. 15B

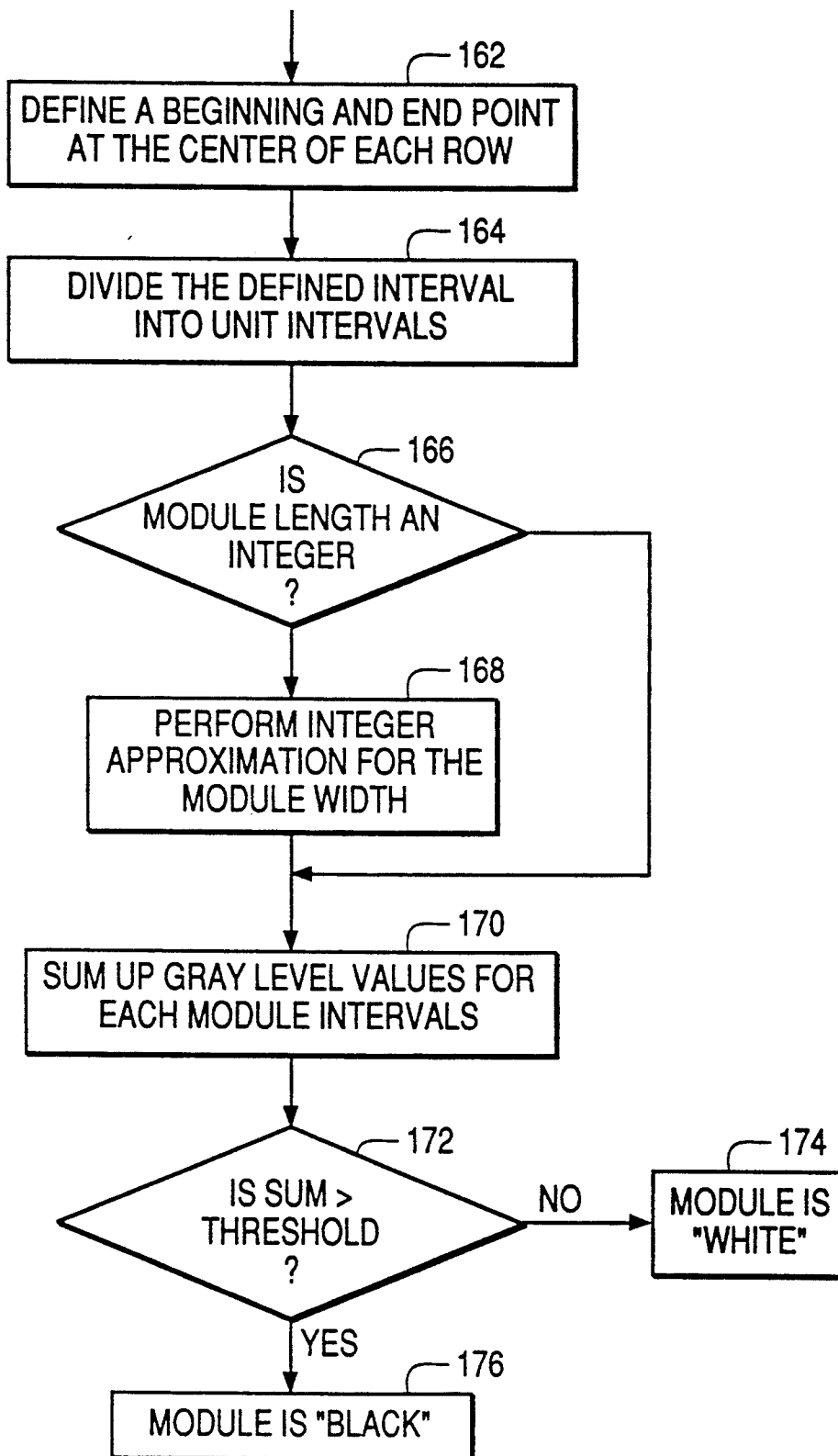


FIG. 16

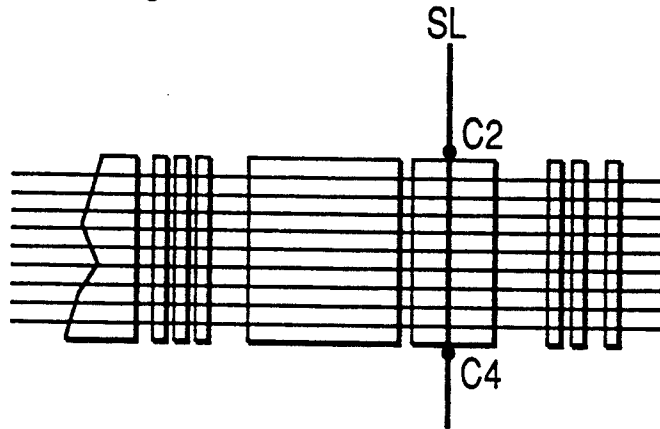
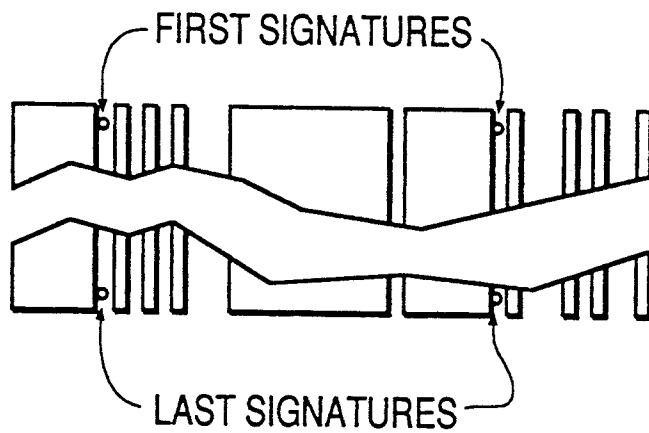


FIG. 17



METHOD AND APPARATUS FOR DECODING TWO-DIMENSIONAL BAR CODE USING CCD/CMD CAMERA

BACKGROUND OF THE INVENTION

The present invention generally relates to the field of bar code readers, and more particularly to a method and apparatus for scanning and decoding a two-dimensional bar code such as PDF417 using a charge-coupled device (CCD) camera or a charge modulation device (CMD) camera.

Bar codes have become broadly accepted as a means for automatically identifying objects. A bar code symbol is a pattern of parallel bars and spaces of various widths that represent data elements or characters. The bars represent strings of binary ones and the spaces represent strings of binary zeros. Generally, the bars and spaces can be no smaller than a specified minimum width which is called a "module" or "unit." The bars and spaces are multiples of this module size or minimum width.

The conventional bar code symbol is "one-dimensional" in that the bars and spaces extend only in a single direction. There has been an increasing need, however, for machine-readable symbols that contain more information than conventional bar code symbols. One approach for increasing the information in machine-readable symbols is to reduce the height of the bar codes and stack the bar codes one on top of each other to create a "stacked" or "two-dimensional" bar code. One such two-dimensional bar code is PDF417, which was developed by Symbol Technologies, Inc. A complete description of the PDF417 code is contained in U.S. patent application Ser. No. 07/461,881, filed Jan. 5, 1990 and assigned to the same assignee as the present invention, which is hereby incorporated by reference.

Bar code symbols are typically read by optical techniques, such as scanning laser beams, and the resulting electrical signals are then decoded to recover the data encoded in the symbol. When decoding a two-dimensional bar code symbol, however, laser scanners have the disadvantage that the scan lines must be substantially aligned with the rows of the symbol. Although a two-dimensional bar code such as PDF417 allows some deviation, the orientation of the scan lines must still be less than a maximum angle relative to the rows of the symbol.

There are many applications, however, in which it is desirable to be able to read and decode a two-dimensional bar code symbol in any orientation without having to align the reader with rows of the symbol. For example, in an industrial environment, the symbol may be located on an object moving along a conveyor belt where the reader views the symbol from above. Thus, the symbol may be in any orientation relative to the reader.

In addition, it is often desirable to be able to read a code symbol that has defects. For example, handling may cause a corner of a symbol to be torn off, or a stain or scratch may obscure part of a symbol.

SUMMARY OF THE INVENTION

Accordingly, it is a goal of this invention to provide a method and apparatus for reading and decoding a two-dimensional bar code symbol in any orientation.

Another goal is to provide a method and apparatus for reading and decoding a two-dimensional bar code

symbol even though the symbol has various defects, such as a damaged corner, a scratch, or a stain, which partially obscure the symbol.

These and other goals may be achieved by using a two-dimensional CCD/CMD camera to obtain an image of the two-dimensional bar code symbol, converting the image to a digital representation, and then storing the image data in a memory. Since the image remains unchanged in the memory, it can be accessed repetitively to extract different spatial information. In addition, a CCD camera can perform omnidirectional reading or enlarge a tiny label by using a microphoto lens. A CCD/CMD camera also can read a label from greater distances using a telephoto lens.

Once the image data is stored in the memory, the location and orientation of the bar code symbol are located within the image data. In particular, the four corners of the symbol are located and then checked to see that they form a rectangle. The image data is then converted to the same format as data obtained from a laser scanner by performing "virtual scanning" of the image data across the rows of the symbol. This data can then be decoded in the same manner as data obtained from a laser scanner.

More specifically, a method for decoding a two-dimensional bar code symbol having codewords of bar coded information including a start and a stop codeword, the codewords being formed of a plurality of modules, comprises the steps of: taking a picture of the two-dimensional bar code symbol, converting the picture to lines of image data, and storing the image data in a memory; determining an orientation of the two-dimensional bar code symbol in the image data by locating at least one of the start and stop codewords; determining a sequence of lines passing through the rows of the bar code symbol; and scanning the two-dimensional bar code symbol along the sequence of lines to read the codewords.

In addition, an apparatus for decoding a two-dimensional bar code symbol having codewords of bar coded information including a start and a stop codeword, the codewords being formed of a plurality of modules, comprises: means for taking a picture of the two-dimensional bar code symbol, converting the picture to lines of image data, and storing the image data in a memory; means for determining an orientation of the two-dimensional bar code symbol in the image data by locating at least one of the start and stop codewords; means for determining a sequence of lines passing through the rows of the bar code symbol; and means for scanning the two-dimensional bar code symbol along the sequence of lines to read the codewords.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention as claimed.

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate an embodiment of the invention and together with the general description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram illustrating the modules and sequence of bars and spaces forming a codeword;

FIG. 2 is a block diagram showing the overall structure of a PDF417 symbol;

FIG. 3 is a block diagram illustrating one embodiment of a system for reading a two-dimensional bar code symbol using a CCD/CMD camera;

FIG. 4 is a schematic block diagram of one embodiment of the hardware apparatus of a decoder;

FIG. 5 is a diagram illustrating scanning of data along a given row of an image;

FIG. 6 is a diagram illustrating the determination of the location of the start pattern of the symbol;

FIG. 7 is a diagram illustrating the determination of the top and bottom of the symbol;

FIG. 8A is a flowchart showing the operation sequence of the decoder for determining the location and orientation of the symbol within the image data;

FIG. 8B is a flowchart showing the operation sequence of the decoder for verifying that the four control points actually form a rectangle;

FIG. 9 is a diagram illustrating the determination of the four corners of the symbol and the scanning control lines as well as virtual scan lines;

FIG. 10 is a diagram showing a section of symbol with a start pattern damaged by a torn corner;

FIG. 11 is a diagram showing a section of a symbol damaged by a stain;

FIG. 12 is a diagram illustrating the determination of neighboring lines for each control line;

FIG. 13 is a flowchart showing the operation sequence of the decoder for verifying the control lines and correcting for a corner defect;

FIG. 14 is a diagram illustrating the determination of label width estimation and virtual scan path optimization;

FIGS. 15A and 15B a flowchart showing operation sequence of the decoder for performing virtual scanning of the image data;

FIG. 16 is a diagram illustrating the determination of virtual scan lines when one of the start or stop patterns is damaged; and

FIG. 17 is a diagram showing the decoding of a symbol having a scratch in the middle.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Reference will now be made in detail to the presently preferred embodiment of the invention, an example of which is illustrated in the accompanying drawings.

Code PDF417

Before discussing the preferred method and apparatus for reading and decoding a two-dimensional bar code symbol such as PDF417 using a CCD/CMD camera, it is important to understand the structure of the symbol.

Each PDF417 symbol is composed of a stack of rows of bar-coded information. Each row in the symbol consists of a start pattern, several codewords, and a stop pattern. A codeword is the basic unit for encoding a value representing, or associated with, certain numbers, letters, or other symbols. Collectively, the codewords in each row form data columns.

Both the number of rows and the number of data columns of the PDF417 symbol are variable. The symbol must have at least three rows and may have up to ninety rows. Likewise, within each row, the number of codewords or data columns can vary from three to thirty.

Each PDF417 codeword consists of seventeen modules or units. There are four bars and four spaces in each

codeword. Individual bars or spaces can vary in width from one to six modules, but the combined total per codeword is always seventeen modules. Thus, each codeword can be defined by an eight-digit sequence, which represents the four sets of alternating bar and space widths within the codeword. This is called the "X-sequence" of the codeword and may be represented by the sequence X_0X_1, \dots, X_7 . For example, for an X-sequence of "5111125", the first element is five modules wide, followed by five elements one module wide, one element two modules wide, and the last element five modules wide. This example is illustrated in FIG. 1.

FIG. 2 is a block diagram showing the overall structure of a PDF417 symbol. Each row of the symbol consists of a start pattern, a left row indicator codeword, one or more data codewords, a right row indicator codeword, and a stop pattern. The minimum number of codewords in a row is three, including the left row indicator codeword, at least one data codeword, and the right row indicator codeword.

The start and stop patterns identify where each row of the symbol begins and ends. PDF417 uses unique start and stop patterns. The start pattern, or left side of each row, has the unique pattern, or X-sequence, of "81111113". The stop pattern, or right side of each row, has the unique X-sequence of "71131121". Since the start and stop patterns are the same for each row, these patterns form solid structures on the left and right sides of the symbol, respectively. The entire symbol is surrounded by clear spaces or "quiet zones" which contain no dark marks.

Encoding data into a PDF417 symbol is typically a two-step process. First, data is converted into codeword values which represent the data. This is known as "high-level encoding." The values are then physically represented by particular bar-space patterns, which is known as "low-level encoding."

Scanner/Reader System

FIG. 3 illustrates one embodiment of a system for reading a two-dimensional bar code symbol such as PDF417 using a CCD/CMD camera. As shown in FIG. 3, a bar code reading system 10 includes a host computer 12, which may be a personal computer, a decoder 14, a frame grabber circuit 16, and a two-dimensional CCD or CMD camera 18. CCD/CMD camera 18 takes a picture of a two-dimensional bar code symbol 20 and converts it to electrical signals. Typically, the output of the CCD/CMD camera is an analog signal in a standard RS-170 format representing the rows of the image being captured along with horizontal and vertical synchronization information.

Alternatively, if the two-dimensional bar code symbol is moving past the camera, the CCD/CMD camera could be only a one-dimensional camera. For example, the bar code symbol may be on an object moving past the camera on a conveyor belt or may be printed on a document that is being scanned by the camera. In this case, the CCD/CMD camera can capture the image of the two-dimensional symbol by scanning successive lines of the symbol as it moves past the camera.

Electrical signals from camera 18 are transmitted to frame grabber circuit 16 which converts the signals into a digital representation of the original image. The analog signals from the CCD/CMD camera are converted to eight-bit gray-level values and transmitted to decoder 14 where they are decoded into a matrix of codeword values corresponding to the rows and columns of

the two-dimensional bar code symbol. As explained in further detail below, decoder 14 may be embodied in a computer program operating on a special purpose microprocessor.

The matrix of codeword values from decoder 14 is further decoded into usable data by a high-level decoder, which may be embodied as a separate computer program operating on the host computer 12. For example, PDF417 has three predefined modes and nine reserved modes. The predefined modes are Binary, EXC, and Numeric. In the Binary mode, each codeword can encode 1.2 bytes. In the EXC mode, the alphanumeric data can be encoded in double density (i.e., two characters per code word), and in Numeric mode, the numeric data can be packed in almost triple density. Therefore, the high-level decoder in host computer 12 will further decode the codeword values from low-level decoder 14, depending on the mode, to obtain the actual data embodied in the symbol. The decoded data from the high-level decoder may then be used by a user application program also operating on the host computer 12.

Decoder Apparatus

FIG. 4 is a schematic block diagram of one embodiment of the hardware apparatus of decoder 14. As shown in FIG. 4, decoder 14 includes a FIFO (first in-first out) memory buffer 22 for receiving the digital data representing the image of the two-dimensional bar code from the frame grabber circuit 16. The FIFO buffer 22 temporarily holds the data as it is received from the frame grabber circuit 16 and then stores it in a memory 24. In order to do this, FIFO buffer 22 is connected to a central bus 23 to which the other hardware elements of the low-level decoder are also connected. FIFO buffer 22 has direct memory access (DMA) capability which allows it to store the digital data directly in the memory for decoding. Alternatively, the frame grabber circuit 16 could be connected directly to the bus 23 with DMA capability and thereby store the digital data directly in the memory 24.

The decoder also includes a central processing unit (CPU) 25 and a second interface 26 for communicating with the host computer. The CPU 25 is preferably a high-speed special purpose microprocessor such as the TMS 320 digital signal processor. The interface to the host computer may be a standard interface such as an RS-232 interface.

Decoder Operation

Determining Symbol Location and Orientation

The first task that must be performed by the decoder in decoding a two-dimensional bar code symbol such as PDF417 is to find the location and orientation of the symbol in the image data.

Finding the location and orientation of the symbol is based on finding the start and stop patterns of the symbol in the image data. Operating on the image data stored in the memory, the decoder scans the data along a given row of the image as shown in FIG. 5. The data along the row is passed through an edge detector which determines the locations of the edges in the data. The decoder then searches through the edge detection data looking for a sequence of eight elements that represent either a start or stop pattern.

The decoder starts at the top of the image data scanning the first row. Then, in subsequent scans of the image data, it moves down a predetermined number of rows and scans that row looking for start or stop pat-

terns. The number of rows between successive scan lines may vary according to the particular environment or the resolution of the image data. For example, where the image data consists of 480 rows by 640 columns of pixel data, the decoder may be set to scan every twentieth row, skipping nineteen rows between successive scan lines.

If at least two start patterns or two stop patterns are found, then the orientation of the symbol can be determined. For example, as shown in FIG. 5, the two points p1 and p2 represent the locations of two start patterns and the two points q1 and q2 represent the locations of two stop patterns. A straight line perpendicular to the rows of the symbol can be drawn through the two points as shown in FIG. 6 to determine the orientation of the symbol.

Although theoretically two such points are sufficient to determine a straight line, the decoder will try to accumulate more than two start or stop patterns, up to a predetermined limit. The decoder will then select the two "best" patterns for finding the orientation of the symbol. The best patterns are considered to be those start or stop patterns which have no defects and are as far apart as possible.

If the decoder is unable to detect two start patterns or two stop patterns while scanning horizontally across the rows, then the decoder will scan the image data vertically down the columns looking for start or stop patterns. If the decoder is still unable to detect at least two start patterns or two stop patterns in either the horizontal or vertical direction, then the camera takes a new picture and the decoding process starts over.

If the decoder is successful in detecting at least two start patterns and two stop patterns in the image data, the decoder then attempts to determine the location of four control points C1, C2, C3, and C4 at the top and bottom of the start and stop patterns as shown in FIG. 7. For the start pattern, this is done by first determining a straight line SL1 through the center of the first bar of the start pattern. Then starting from two points located inside the first bar, the decoder searches outward along the line SL1 for the edges of the symbol. The edges of the symbol are determined by a large change in the gray level of the pixel data along this line. The two edge points found in this way are the control points C1 and C2. A similar procedure is carried out for the stop code word along line SL2 to find the other two control points C3 and C4.

FIG. 8A is a flowchart showing the sequence of operation of the decoder for determining the location and the orientation of the symbol within the image data. The various steps in the sequence are embodied in a software computer program which is stored in memory 24 and executed by CPU 25 shown in FIG. 4.

As shown in FIG. 8A, determination of symbol location and orientation begins by a horizontal scan of the image data in step 30. Before searching for the start or stop patterns edge locations of the symbol are determined in step 32.

The edges are determined by traversing a line between two end points and searching for an edge along the line. In particular, the slope of the line is first determined, and starting from the first end point of the line, the value or the gray level of a current pixel on the line is compared with the value of the previous pixel. If the compared value is greater than or equal to a predetermined threshold value, then the edge is at the current

pixel position. If the compared value is less than the predetermined threshold value, then the current pixel position is incremented according to the slope of the line and the incremented position becomes the new current pixel position. The current pixel position (the incremented position) is compared with the last pixel position. This procedure is continued until either an edge is found, or the current pixel position reaches the last end point of the line.

Once the edges have been determined, in step 34 a start or a stop pattern is searched for in the edge location data. To find the start pattern, eight successive numbers are read. The first number, however, must be a bar. If it is not, then the next eight successive numbers are read. If the first number is a bar, then the first four numbers are determined. The eight numbers are normalized by divided by the sum of eight values, multiplying by 17 and then rounding to the nearest interest. The result is then compared to the start and stop patterns. If it matches one of those then the pattern is found. If any of the conditions are not met, then the next eight successive numbers are read.

If the start or stop pattern is found in step 36, then the counter is incremented in step 38 and a selected number of rows are skipped, as indicated in step 46. Afterwards, the next horizontal scan of image data is begun.

If a start or stop pattern is not found in step 36, then determination is made whether there are any additional rows to be scanned. If so, a selected number of rows are skipped step 46, and the horizontal scan of image data is repeated.

If there are no additional rows to be scanned, then a determination is made of whether multiple stop or start patterns had been found in step 45. If not, a vertical scan of image data is begun in step 48, and in step 50, the location of edges is determined as it was during the horizontal scan. Again, there is a search for start or stop pattern in the edge location data in step 52, similar to the one in step 34 for the horizontal scan, and in step 44, a determination is made whether a start or stop pattern is found. If so, then the counter is incremented in step 56, and a selected number of columns is skipped in step 64. Afterwards, the vertical scan of image data repeats.

If a start or stop pattern was not found in step 54, then a determination is made whether there are any additional columns to be scanned in step 62. If so, a selected rows are skipped in step 64, and the vertical scan of image data continues. If there are no additional columns to be scanned, then a determination is made whether there are multiple start and stop patterns found in step 63. If not, then a new image of the data is taken as indicated in step 66, and a horizontal scan begins at step 30.

If, in steps 45 or 63 there were multiple stop or start commands found, then the two best start or stop patterns are selected in steps 42 or 60, respectively. Based on the two best start and stop patterns selected in either in steps 42 or 60, the four control points are determined in step 68.

To determine the four control points, a line is drawn passing through the middle of the first bar of both start and stop patterns. A control point lies at a point having a large gray-level change on each line. Therefore, a control point exists along the line at the top and bottom of the first bar of the start pattern and at the top and bottom of the first bar of the stop pattern.

Verifying Symbol Location and Orientation

Once the four control points are determined, the decoder then checks to see that the location and orientation of the symbol form a rectangle. This is done by verifying that adjacent sides of the symbol are at right angles to each other. Two lines are at right angles if their slopes S_1 and S_2 are related as follows:

$$S_1 = -S_2^{-1}$$

FIG. 8B is a flowchart showing the sequence of operation of the decoder for verifying that the four control points C1, C2, C3, and C4 actually represent a rectangle.

Using for four control points determined in FIG. 8A, a rectangle is formed in step 70 by the lines L_1 , L_2 , L_3 , and L_4 connecting those control points. In step 72, the slopes of the intersecting lines are determined by converting them into vectors. Specifically, for lines L_1 and L_2 that intersection at point (x_2, y_2) , the line L_1 and line L_2 would be defined as follows:

$$L_1: \{(x_1, y_1), (x_2, y_2)\}$$

$$L_2: \{(x_2, y_2), (x_3, y_3)\}$$

Lines L_1 and L_2 are perpendicular if their inner product, or dot product, is zero. The inner product of L_1 and L_2 is defined as follows:

$$\langle L_1, L_2 \rangle = (x_2 - x_1)(x_3 - x_2) - (y_2 - y_1)(y_3 - y_2).$$

In practice, the absolute value of the inner product of lines L_1 and L_2 is compared to a small positive number ϵ . If the absolute value of the inner product of L_1 and L_2 , $|\langle L_1, L_2 \rangle|$, is less than ϵ , then, as step 76 indicates, lines L_1 and L_2 are deemed to be perpendicular. If L_1 and L_2 are perpendicular, then L_2 is compared to L_3 (step 78), and perhaps L_3 is compared to L_4 (step 80) and L_4 is compared to L_1 (step 82). If all the lines are perpendicular, then the conclusion reached in step 84 that the symbol is rectangular. As soon as any two adjacent lines are determined not to be rectangular, the symbol is deemed not rectangular (step 86).

Corner Defect Correction

If the four control points C1, C2, C3, and C4 do not form a rectangle, then it is most likely that one or more of the corners is damaged.

First, the decoder determines two control lines CL1 and CL2 along the top and bottom edges of the symbol as shown in FIG. 10. The decoder then checks to see if each of the control lines CL1 and CL2 have been determined correctly. For example, if one of the corners is torn away (FIG. 10) or obliterated by a stain (FIG. 11), one of the control lines will be incorrect.

In order to determine whether a control line is correct, the decoder will determine, for that control line, two neighboring lines, both parallel to the control line and on opposite sides as shown by the dotted lines in FIG. 12. The neighboring lines are a predetermined distance, such as five pixels, away from the control line. If the control line is correct, then one of the neighboring lines should contain both a start and a stop pattern and the other neighboring line should contain neither.

Once it is determined that one control line is correct, the other control line (e.g., CL1 in FIG. 12) will be corrected so to be parallel to the correct control line

(e.g., CL2 in FIG. 2). The new control line can then be verified by determining two neighboring lines as before. If the new control line (CL1) is correct, then one of its neighboring lines must contain either a start or a stop pattern, while the other neighboring line must contain neither.

FIG. 13 is a flowchart showing the sequence of operation of the decoder for verifying the control lines and correcting for a corner defect. In the decoder operation, the damaged corner is adjusted towards a non-damaged corner by this routine which first checks a stop line and then a start line. Although this sequence is arbitrary, it is significant that both lines are tested. If both points on the start or stop lines are damaged, then the routine attempts to adjust the corner point which is relatively lower to the other point by measuring the length of the lines C₁, C₂ (see FIG. 10) and C₃ C₃ and C₃ C₄. In the routine, line C₃ C₄ is longer than C₁ C₂, so C₁ is adjusted to be the height of C₃.

In step 90, top and bottom control lines are drawn, and in step 92 two parallel neighboring lines are drawn for each control line. In the manner described above, the start and stop patterns are found, if possible, on each neighboring line in step 94. This is to see whether the control lines are valid in the manner described above.

If in step 96 one of the control lines is determined to be valid, then in step 98, a question is asked whether the other control line is valid. If not, then in step 102 a determination is made that both control lines are invalid.

If in step 96 one of the control lines is valid, and in step 100 the other control line is determined to be valid, then the conclusion is reached in step 104 that both control lines are valid.

If, as a result of the determinations in steps 98 and 100, only one of the control lines is determined to be valid, this is noted in step 106, and in step 108, the invalid control line is corrected to become parallel with the valid control line, as described above.

Next, the corrected control line is tested in step 110. If the corrected control lines are both valid in step 112, then in step 116, determination can be made that the invalid control line has been corrected. Otherwise, in step 114, a determination is made that the invalid control line cannot be corrected.

Virtual Scanning

Once the four control points that define the location and orientation of the label have been determined, the decoder performs "virtual scanning" of the image data stored in the memory. This involves selecting a sequence of pixels from the image data that cross the symbol from the start pattern to the stop pattern parallel to a line defining the top of the symbol. Thus, the data obtained in this way will represent a scan along a row of the symbol.

This sequence of pixel data is sent through an edge detector to determine the locations of the transitions from dark to light or light to dark in the symbol. The transitions are then used to determine the width of the bars and spaces in the symbol. The sequence of data corresponding to the width of the bars and spaces in symbols is in the same format as data obtained from a laser scanner.

More specifically, once the four control points C₁, C₂, C₃, and C₄ are determined, the decoder determines the location of control lines CL1 and CL2 as shown in FIG. 9. Then, a virtual scan start line VSL1 and a res-

can stop line VSL2 are determined. Line VSL1 is parallel to the start pattern and passes through the quiet zone adjacent the start pattern. Likewise, line VSL2 is parallel to the stop pattern and passes through the quiet zone adjacent the stop pattern.

In order to scan a row of the symbol in the image data, the decoder identifies both the head point on the scan start line VSL1 and the corresponding tail point on the scan stop line VSL2. The scan head and tail points may be all the points on the line segments of RSL1 and RSL2 between the control lines CL1 and CL2. Alternatively, as explained in further detail below, the number of scan lines may be minimized by using a rescan optimization strategy. Point positions for the rescan head and tail points are stored in an array for rescanning the image data.

For each scan "head-tail" point pair, the decoder scans along a line from the scan head point to the scan tail point. A typical scan line is shown in FIG. 9 scanning from scan head point h_i to scan tail point t_i . The decoder fetches the gray-level values along the line from the image data. This line of data is then processed to obtain the required output data format.

One way to obtain the output data from the gray-level values is to use edge detection. Using this method, the decoder first calculates the difference between successive gray-level values along the rescan line. The decoder then looks for extrema within a specified neighborhood, such as a window of three pixels, in the sequence of difference values. Edges are determined to be where the magnitude of an extremum of the difference values exceeds a predetermined threshold. The widths of the bars and spaces are then computed by determining the distance between the edges.

Alternatively, if the number of codewords in each row are known or have been determined from decoding part of the symbol, the width of the bars and spaces can be determined by applying a binary decision on the gray-level values of the rescan line. In this procedure, only those gray-level values on a rescan line that passes through the middle of a row are used to make a binary decision.

First, the decoder determines the beginning point B of the first codeword and the end point E of the last codeword, excluding the start and stop patterns. The whole interval (B, E) is then divided into unit intervals I_k . Specifically, the number of pixels in the line is divided by the total number of modules in the row, which is equivalent to the number of codewords times the number of modules per codeword, in order to obtain the average module length u . Typically the average module length u will not be an integer, so it becomes necessary to assign an approximated module length for each module in the row of codewords.

If the module length u is not an integer, it will necessarily fall between two integers. Therefore, for each module length there exists an integer k such that

$$k < u < k + 1$$

Therefore, there are two ways to assign an approximated module length value for each module, namely picking one of either k or $k + 1$. If k is picked, then this results in an approximation error of

$$e_k = u - k$$

If $k+1$ is picked, this results in an approximation error of

$$e_k = -(k+1-u)$$

The selected integer value, either k or $k+1$, is therefore the one that minimizes the accumulated approximation error, where the accumulated approximation error up to the k th module is given by:

$$\text{Accumulated error} = \sum_{i=0}^k e_i$$

Once the width of each module is determined, the decoder can decide whether each module is either black or white by applying a binary decision to the gray-level values of the module. Specifically, the gray-level values in each module are summed up and compared with a predetermined threshold to make the decision whether the module is black or white.

As discussed above, the decoder may scan every possible rescan line between lines CL1 and CL2. Although this strategy results in the maximum amount of information for decoding the symbol, there is a significant amount of overhead because one rescan line is sufficient for each row if the line is determined correctly.

Therefore, the number and location of the scan lines may be optimized based on the following considerations:

(1) Two adjacent rescan lines inside the same row of the symbol (SL1 and SL2 in FIG. 14) should have the same gray-level profiles, except for a small amount of deviation due to noise;

(2) Two adjacent rescan lines from different rows of the symbol (SL2 and SL3 in FIG. 14) should have a large "distance" between their gray-level profiles; and

(3) The distance measure $D(S1, S2)$ between two rescan lines S1 and S2 is defined as the sum of all distances between corresponding pixels on the lines, where the distance $d(S1[i], S2[i])$ between respective pixels S1[i] and S2[i] is determined as follows:

$$d(S1[i], S2[i]) = \begin{cases} 0 & \text{if } |S1[i] - S2[i]| < T \\ 1 & \text{if } |S1[i] - S2[i]| > T, \end{cases}$$

where T is a predetermined threshold. Therefore, the gray-level distance between two rescan lines S1 and S2 is determined as follows:

$$D(S1, S2) = \sum d(S1[i], S2[i])$$

Accordingly, $D(S1, S2)$ will be small when two adjacent rescan lines are near the middle of a row and will be large when two adjacent rescan lines are crossing the boundary between adjacent rows.

In order to optimize the scan paths, the decoder first computes the distance between successive segments of all possible rescan lines. The length of the line segments should be long enough to cover at least one codeword as shown in FIG. 14. Using segments instead of whole rescan lines greatly reduces the computation time. When all of the distances have been computed, the rescan lines can be laid where the distance is a local minimum, corresponding to the middle of row of the symbol.

FIGS. 15A and 15B are flowcharts showing the sequence of operation of the decoder for performing virtual scanning of the image data.

FIG. 15A is a flow chart illustrating the edge detection method of outputting the image data. As shown in FIG. 15A, once the location of control lines have been determined (step 120), a pair of head-tail points is retrieved in step 130. In step 132, a rescan line is drawn by connecting the pair of head-tail points. The differences between the gray levels are computed along the rescan line in step 134.

In step 136, extrema of the difference values are determined within a specified neighborhood (usually a window of 3 pixels). The extrema are determined by locating and recording the maximum and minimum values within a neighborhood or window of a specified point. If the magnitude of the located maximum or minimum value is large enough and the position is not at the boundary of the neighborhood, then that position is considered as an extremum.

In step 138, each extremum is compared with a predetermined threshold value to determine whether the extremum is an edge. If the extremum is greater than the threshold, then in step 140 that extremum is indicated as an edge. Otherwise, in step 142 the extremum is indicated as not being an edge. In step 150, distances between the determined edges (output sequence) are computed and sent to the low level decoder. The above steps are repeated until no more head-tail points remain (step 152).

FIG. 15B is a flow chart illustrating a center sampling and binary decision method of outputting the image data. This method uses the data on the start and stop patterns, control points, label row width, and width of modules.

In step 162 of FIG. 15B, a beginning point B of the first non-start/stop codeword and an end point E of the last non-start/stop codeword are defined. In step 164, the interval between the two points B-E are divided into predetermined unit intervals. If the module width is a non-integer number, then an integer approximation routine is performed for the module width in step 168. The errors associated with the approximation were explained previously.

Once the interval B-E have been divided, the gray-level value for each module interval is summed up in step 170 and compared with a predetermined threshold in step 172. If the sum is greater than the threshold number, then the module is considered to be "black." If not, the module is considered to be "white." Therefore, according to the sequences of black and white mo e output of image data is produced.

The data obtained by rescanning the image data is output to a low-level decoder for further decoding the data. A low-level decoder for decoding a two-dimensional symbol such as PDF417 is described in U.S. patent application Ser. No. 07/851,404, entitled "A System for Encoding and Decoding Data In machine Readable Graphic Form," filed the same date as this application and assigned to the same assignee as the present invention, which is hereby incorporated by reference.

Damaged Symbols

In addition to the corner defects described above, the (bar code symbols may be damaged in other ways. For example, lone of the start or stop patterns may be damaged. If the other pattern can still be identified, how-

ever, then the decoder will determine only two of the four control points C1, C2, C3, and C4. In the example shown in FIG. 16, where the start pattern of the symbol is destroyed, the decoder will determine only control points C2 and C4.

From these two control points, the decoder will then determine a single line SL as shown in FIG. 16. Once SL is obtained, a set of rescan lines can be determined between the two control points, each one perpendicular to the line SL.

This procedure necessarily assumes, however, that the frame grabber causes no geometric distortion (i.e., essentially square pixels). If the rectangular shape of the symbol is distorted into a parallelogram, then this procedure will not work.

The decoder may also decode symbols that have a scratch in the middle such as shown in FIG. 17. Since the decoder begins searching for the two control points from the farthest valid start or stop patterns, a scratch in the middle should not affect the locating of control points. However, each of the remaining corners must be read by at least one scan line while trying to determine the location and orientation of the symbol.

It will be apparent to those skilled in the art that various modifications and variations can be made in the decoding method and apparatus without departing from the scope or spirit of the invention. Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

What is claimed is:

1. A method for decoding a two-dimensional bar code symbol having rows of bar coded information in which data is represented in each row by a plurality of codewords, each row including a predetermined control codeword which is the same for each row, the codewords being formed of a plurality of modules, the method comprising the steps of:
 - optically imaging the two-dimensional bar code symbol, converting the image to lines of image data corresponding to a field of view including the bar code symbol, and storing the image data in a memory;
 - determining an orientation of the two-dimensional bar code symbol in the field of view by locating the positions of at least two of the control codewords in the image data;
 - determining a sequence of lines passing through the rows of the bar code symbol in the image data from the orientation derived from the positions of the control codewords; and
 - scanning the two-dimensional bar code symbol in the image data along the sequence of lines to read the codewords.
2. The method of decoding a two-dimensional bar code symbol according to claim 1, further comprising the steps of
 - detecting defects on the two-dimensional bar code symbol; and
 - scanning the two-dimensional bar code symbol properly despite the presence of defects.
3. The method of decoding a two-dimensional bar code symbol according to claim 1, wherein the orientation determining step comprises the steps of:

scanning the lines of image data to determine edge locations of the symbol;
 searching for control codewords along the edge locations of the symbol in the image data; and
 determining a plurality of control points adjacent the symbol in the image data relative to the positions of the control codewords.

4. The method for decoding a two-dimensional bar code symbol according to claim 3, further comprising the step of verifying the orientation of the two-dimensional bar code symbol.

5. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein the image data scanning step includes a horizontal scan.

6. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein the image data scanning step includes a vertical scan.

7. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein the image data scanning step includes skipping a predetermined number of lines while searching for the control codewords.

8. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein each row of the symbol includes two predetermined control codewords, one control codeword being a start codeword at the beginning of each row and the other control codeword being a stop control codeword at the end of each row, and wherein the searching step is repeated until a predetermined number of start and stop codewords have been found.

9. The method for decoding a two-dimensional bar code symbol according to claim 8, further comprising the step of selecting the best two start and best two stop codewords from the predetermined number of located start and stop codewords.

10. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein the image data scanning step for determining the edge locations includes the steps of:

- selecting two end points to find edge locations therebetween;
- traversing a line between the two end points;
- calculating a slope of the line;
- comparing a gray level of a first pixel position to a second pixel position on said line;
- determining the first pixel position to be an edge location when the comparison is greater than or equal to a first predetermined threshold value;
- incrementing said first and second pixel positions along said line according to said slope; and
- repeating said comparison step until the last end point is reached.

11. The method for decoding a two-dimensional bar code symbol according to claim 3, wherein the control point determining step comprises the steps of:

- determining a line passing through a first bar of the control codewords; and
- locating points both on said line and at an edge of the two-dimensional bar code symbol.

12. The method for decoding a two-dimensional bar code symbol according to claim 4, wherein the verifying step includes checking whether the two-dimensional bar code symbol forms a rectangle having a shape meeting requirements of a first predefined acceptable condition.

13. The method for decoding a two-dimensional bar code symbol according to claim 12, wherein the checking step comprises the steps of:

connecting the control points to form a rectangle;
calculating a slope for each line of said rectangle; and
comparing the slopes of intersecting lines at each corner of said rectangle, wherein the symbol has the acceptable rectangular shape when each of said comparison at said each corner of said rectangle is less than a second predetermined threshold value.

14. The method for decoding a two-dimensional bar code symbol according to claim 2, wherein each row of the symbol includes two predetermined control codewords, one control codeword being a start codeword at the beginning of each row and the other control codeword being a stop control codeword at the end of each row, and wherein the detecting step comprises the steps of:

determining a control line at top and bottom edges of the symbol;
forming first and second neighboring lines adjacent and at opposite sides of each said control lines;
searching for the start and stop codewords on each side neighboring lines; and
determining the symbol to have a defect when each said control line fails to meet predefined conditions.

15. The method for decoding a two-dimensional bar code symbol according to claim 14, wherein the second predefined condition includes said first neighboring line having both start and stop codewords and said second neighboring line having neither of the start and stop codewords.

16. The method for decoding a two-dimensional bar code symbol according to claim 14, wherein the correcting step corrects for one defective control line with the other control line being a valid control line, the correcting step comprising the step of adjusting the defective control line to be parallel with the valid control line and to include one of the control points.

17. The method for decoding a two-dimensional bar code symbol according to claim 16, further comprising the step of validating the adjusted control line, said validating step including the step of:

forming two neighboring lines adjacent and at opposite sides of said adjusted control lines;
searching for one of said start and stop codewords on each said neighboring lines; and
determining the valid correction of the defective control line by testing whether said adjusted control line meets a condition of having one neighboring line having one of start and stop codewords and the other neighboring line having neither of the start and stop codewords.

18. The method for decoding a two-dimensional bar code symbol according to claim 1, wherein the line determining step comprises the steps of:

forming rescan start and rescan stop lines;
selecting virtual scan head and corresponding virtual scan tail points on said rescan start and scan stop lines, respectively; and
retrieving a pair of head and corresponding tail points and forming a line connecting the two points.

19. The method for decoding a two-dimensional bar code symbol according to claim 18, wherein the scanning step comprises the steps of:

computing gray-level differences between successive pixels on said line connecting the head and tail points;

finding extreme of the computed differences;

comparing each extremum to a third predetermined threshold value;

determining the extremum to be an edge when the comparison is greater than said third predetermined threshold value; and

calculating distances between adjacent edges.

20. The method for decoding a two-dimensional bar code symbol according to claim 19, wherein the scanning step further comprises the step of optimizing the scanning step to reduce the scanning time and overhead by reducing the number of head and tail pairs.

21. The method for decoding a two-dimensional bar code symbol according to claim 1, wherein the line determining step comprises the steps of:

defining an interval having a beginning point and an end point at a center of each row of said two-dimensional bar code symbol and forming a line connecting the beginning and end points;

partitioning the defined interval into a predetermined unit sub-intervals; and

approximating width of the modules to correspond to a nearest unit sub-interval.

22. The method for decoding a two-dimensional bar code symbol according to claim 21, wherein the scanning step comprises the steps of:

summing gray-level values for each module interval;
comparing the sum to a fourth predetermined threshold value; and

determining the module to be one of a plurality of predefined values corresponding to the comparison.

23. The method for decoding a two-dimensional bar code symbol according to claim 1, further comprising the step of detecting and correcting damages due to destruction of one of the start and stop codewords of the symbol.

24. An apparatus for decoding a two-dimensional bar code symbol having rows of bar coded information in which data is represented in each row by a plurality of codewords, each row including a predetermined control codeword, the codewords being formed of a plurality of modules, comprising:

means for optically imaging the two-dimensional bar code symbol, converting the image to lines of image data corresponding to a field of view including the bar code symbol, and storing the image data in a memory;

means for determining an orientation of the two-dimensional bar code symbol in the field of view by locating the positions of at least two of the control codewords in the image data; and

means for determining a sequence of lines passing through the rows of the bar code symbol in the image data from the orientation derived from the positions of the control codewords; and

means for scanning the two-dimensional bar code symbol in the image data along the sequence of lines line to read the codewords.

25. The apparatus for decoding a two-dimensional bar code symbol according to claim 24, further comprising means for detecting defects on the two-dimensional bar code symbol and correcting the detected defects on the two-dimensional bar code symbol.

26. The apparatus for decoding a two-dimensional bar code symbol according to claim 24, wherein the orientation determining means comprises:

- means for scanning the lines of image data to determine edge locations of the symbol;
- means for searching for control codewords along the edge locations of the symbol in the image data; and
- means for determining a plurality of control points adjacent the symbol in the image data relative to the positions of the control codewords.

27. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, further comprising means for verifying the orientation of the two-dimensional bar code symbol.

28. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein the image data scanning means includes means for scanning the image data horizontally.

29. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein the image data scanning means includes means for scanning the image data vertically.

30. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein the image data scanning means includes means for skipping a predetermined number of lines while searching for the control codewords.

31. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein each row of the symbol includes two predetermined control codewords, one control codeword being a start codeword at the beginning of each row and the other control codeword being a stop control codeword at the end of each row, and wherein the search for the control codewords in the searching means is repeated until a predetermined number of start and stop codewords have been found.

32. The apparatus for decoding a two-dimensional bar code symbol according to claim 31, further comprising means for selecting the best two start and best two stop codewords from the predetermined number of located start and stop codewords.

33. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein the image data scanning means for determining the edge locations includes:

- means for selecting two end points to find edge locations therebetween;
- means for traversing a line between the two end points;
- means for calculating a slope of the line;
- means for comparing a gray level of a first pixel position to a second pixel position on said line;
- means for determining the first pixel position to be an edge location when the comparison is greater than or equal to a first predetermined threshold value;
- means for incrementing said first and second pixel positions along said line according to said slope; and
- means for repeating the comparison in said comparing means until the last end point is reached.

34. The apparatus for decoding a two-dimensional bar code symbol according to claim 26, wherein the control point determining means comprises:

- means for determining a line passing through a first bar of the control codewords; and
- means for locating points both on said line and at an edge of the two-dimensional bar code symbol.

35. The apparatus for decoding a two-dimensional bar code symbol according to claim 27, wherein the verifying means includes means for checking whether the two-dimensional bar code symbol forms a rectangle having a shape meeting requirements of a first predefined acceptable condition.

36. The apparatus for decoding a two-dimensional bar code symbol according to claim 35, wherein the checking means comprises:

- means for connecting the control points to form a rectangle;
- means for calculating a slope for each line of said rectangle; and
- means for comparing the slopes of intersecting lines at each corner of said rectangle, wherein the symbol has the acceptable rectangular shape when each of said comparison at said each corner of said rectangle is less than a second predetermined threshold value.

37. The apparatus for decoding a two-dimensional bar code symbol according to claim 25, wherein each row of the symbol includes two predetermined control codewords, one control codeword being a start codeword at the beginning of each row and the other control codeword being a stop control codeword at the end of each row, and wherein the detecting means comprises:

- means for determining a control line at top and bottom edges of the symbol;
- means for forming first and second neighboring lines adjacent and at opposite sides of each said control lines;
- means for searching for the start and stop codewords on each said neighboring lines; and
- means for determining the symbol to have a defect when each said control line fails to meet second predefined conditions.

38. The apparatus for decoding a two-dimensional bar code symbol according to claim 37, wherein the second predefined condition includes said first neighboring line having both start and stop codewords and said second neighboring line having neither of the start and stop codewords.

39. The apparatus for decoding a two-dimensional bar code symbol according to claim 37, wherein the correcting means corrects for one defective control line with the other control line being a valid control line, the correcting means including means for adjusting the defective control line to be parallel with the valid control line and to include one of the control points.

40. The apparatus for decoding a two-dimensional bar code symbol according to claim 39, further comprising means for validating the adjusted control line, said validating means including:

- means for forming two neighboring lines adjacent and at opposite sides of said adjusted control line;
- means for searching for one of said start and stop codewords on each said neighboring lines; and
- means for determining the valid correction of the defective control line by testing whether said adjusted control line meets a condition of having one neighboring line having one of start and stop codewords and the other neighboring line having neither of the start and stop codewords.

41. The apparatus for decoding a two-dimensional bar code symbol according to claim 24, wherein the line determining means comprises:

- means for forming rescan start and rescan stop lines;

means for selecting rescan head and corresponding rescan tail points on said rescan start and rescan stop lines, respectively; and
 means for retrieving a pair of head and corresponding tail points and forming a line connecting the two points. 5

42. The apparatus for decoding a two-dimensional bar code symbol according to claim 41, wherein the scanning means comprises:
 means for computing gray-level differences between successive pixels on said line connecting the head and tail points; 10
 means for finding extrema of the computed differences;
 means for comparing each extremum to a third predetermined threshold value; 15
 means for determining the extremum to be an edge when the comparison is greater than said third predetermined threshold value; and
 means for calculating distances between adjacent edges. 20

43. The apparatus for decoding a two-dimensional bar code symbol according to claim 41, wherein the scanning means further comprises means for optimizing the scanning of the image data in the scanning means to reduce the scanning time and overhead by reducing the number of head and tail pairs. 25

44. The apparatus for decoding a two-dimensional bar code symbol according to claim 24, wherein the line determining means comprises:
 means for defining an interval having a beginning point and an end point at a center of each row of said two-dimensional bar code symbol and forming a line connecting the beginning and end points;
 means for partitioning the defined interval into a predetermined unit sub-intervals; and
 means for approximating width of the modules to correspond to a nearest unit sub-interval.

45. The apparatus for decoding a two-dimensional bar code symbol according to claim 44, wherein the scanning means comprises:
 means for summing gray-level values for each module interval;
 means for comparing the sum to a fourth predetermined threshold value; and
 means for determining the module to be one of a plurality of predefined values corresponding to the comparison.

46. The apparatus for decoding a two-dimensional bar code symbol according to claim 24, further comprising means for detecting and correcting damages due to destruction of one of the start and stop codewords of the symbol.

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UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,319,181

DATED : June 7, 1994

INVENTOR(S) : Stephen J. Shellhammer et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

- Claim 10, column 14, line 54 change "comparison" to --comparing--.
Claim 14, column 15, line 25 change "side" to --said--.
Claim 14, column 15, line 27 before "predefined" insert --second--.
Claim 17, column 15, line 47 change "lines" to --line--.
Claim 24, column 16, line 63, after "lines" delete --line--.
Claim 27, column 17, line 12 change "symbols" to --symbol--.
Claim 44, column 20, line 9 change "sub-intervals" to --sub-interval--.

Signed and Sealed this

Twenty-seventh Day of September, 1994

Attest:



BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks