White Paper

A new foundation for 1-D barcode reading:

Hotbars™ image analysis technology

A new foundation for 1-D barcode reading: Hotbars™ image analysis technology

By Bill Silver, Senior Vice President & Senior Fellow, Cognex Corporation

Hotbars Background

If contemporary technology has a grand theme, it is that eventually digital will replace analog, and solid state will replace mechanical. Whether it be music or video, publishing or photography, telecommunications or engine control, the story is similar. Mechanical, analog machines have been around for decades, sometimes centuries. They are mature technologies —the kinks have been worked out, the costs have been squeezed as much as possible, the strengths and weaknesses are well understood. The newer solid state, digital challengers at first offer more promise than performance, but with continued innovation and development they come to dominate the market.

So it will be with linear barcode readers. The market is currently dominated by mature, opto-mechanical laser scanners. The barcode printing and presentation conditions needed to achieve acceptable read rates are well known, and the simplicity of 1-D (one dimensional) signal processing makes the reading speed quite acceptable. Lasers are easy to focus and can put lots of light onto one spot on the object, which gives excellent depth of field, and the mechanical scanning systems can cover a wide field of view. Decades of development and competition have reduced the cost about as far as it can go.

The weaknesses of laser scanners are also well known. The necessary scanning mechanics have moving parts and are subject to wear. Because they only see a single scan line at a time, laser scanners have a very limited ability to take advantage of the redundancy inherent in a linear code that would otherwise allow poorly printed or damaged codes to be read. Laser scanners do not form an image of the object, which would be valuable for improving yield by allowing images of misread objects to be recorded. This lack of image formation also means that laser scanners cannot read 2-D (two-dimensional) symbologies.

One challenger to laser scanners uses a line scan camera to create a large 2-D image of an object moving down a conveyer line and on which is affixed one or more barcodes. Line scan barcode readers offer better read rates on damaged or poorly printed codes, and can record images of misread objects. However, the equipment is typically expensive and difficult to set up and maintain. Part of the difficulty arises because line scan systems require opto-mechanical encoders to track conveyer motion, which are subject to wear and replacement.

The all-solid state, digital challenger to opto-mechanical laser scanners uses a 2-D imager, such as might be found in a digital camera, and some form of microprocessor to analyze the images. Image-based barcode readers have no moving parts and promise improved yields on poorly printed or damaged codes, the ability to save images of misread objects, and the ability to read 2-D symbologies. As is typical of new technology, performance has lagged promise.

Challenges to performance have been found in both image formation (lighting and optics) and image analysis. Steady advances in image formation have yielded vast improvements in field of view and depth of field, undercutting a traditional laser strength. High-intensity LEDs can now illuminate a large field of view and permit the short shutter times necessary to freeze motion. Computer-controlled liquid lenses can rapidly focus over a wide range with no motors or other mechanical parts. Inexpensive image sensors, driven by advances in digital photography, can deliver megapixel images at high frame rates. Barcode reader vendors able to take advantage of these advances can provide an image formation system that permits the barcode reader to compete seriously with traditional laser scanners.

Until recently, advances in image analysis have not kept pace with image formation. Inexpensive contemporary systems can provide a few hundred million high-quality pixels per second to the microprocessor, but the image analysis techniques that had been developed previously can neither keep up with the speed nor take advantage of the quality. Over the last two years, I have led a team of engineers at Cognex who have seen this shortfall as an opportunity to lead the transition to digital technology by bringing image-based barcode readers to a level of maturity where performance can overtake that of opto-mechanical laser scanners. The result of this effort is patent-pending Hotbars™ technology, a novel high-performance image analysis system designed specifically to serve as the foundation for the next-generation of Cognex DataMan® barcode readers.

Hotbars is responsible for providing the primary 2-D image analysis capabilities needed for omnidirectional barcode reading: finding barcodes and extracting 1-D signals for decoding.

The system rests on a solid mathematical foundation, uses algorithms that are well-matched to contemporary digital signal processor (DSP) architecture, and benefits from meticulous hand-coding of speed-critical sections of the software. High reliability results from following image analysis guidelines that Cognex has pioneered for the past 30 years in industrial machine vision:

- Design for *photometric invariance*, the property that image analysis results are largely independent of the overall brightness and contrast of an image.
- Avoid thresholds. When they cannot be avoided, prefer fuzzy thresholds to hard ones. When hard thresholds cannot be avoided, postpone them until late in the analysis.
- Maximize the information that can be extracted from an image by understanding and taking advantage of the effects of pixel grid geometry. The pixel grid is an array of squares, like a checkerboard, and is strongly anisotropic, which means that appearance of image features varies as a function of their orientation relative to the squares of the grid. Information is lost when these effects are ignored, and gained when they are properly considered.

Hotbars Finder

The Hotbars finder analyzes a raw source image and produces a list of regions where it is likely that a barcode exists, along with the orientation and other properties of the barcode. The finder is the gatekeeper for the entire system—it determines the regions where decode attempts will be made, and therefore has a profound effect on yield and speed. A barcode cannot be read unless it occupies a region identified by the finder, and any region identified that does not contain a barcode will slow down the system with useless decode attempts. Furthermore, the finder is the only system component that touches every pixel in the source image, which as previously noted, arrives at a brisk pace of a few hundred million per second. Clearly reliability and speed are at a premium.

One method used by prior image-based readers to find barcodes is to mimic laser scanners by laying down in the image a series of *virtual scan lines* along which 1-D signals are extracted for evidence of barcodes. To achieve reasonable speed, these virtual scan lines typically comprise a limited set of orientations, for example multiples of 45°, and a limited set of positions. The vast majority of image pixels are not examined, a shortcut that can lead to failure modes and reduced yield.

The Hotbars finder takes a different approach, using omnidirectional texture analysis to provide more reliable and complete information. Omnidirectional means producing reliable results regardless of the orientation of the barcode. Texture refers to geometric properties of image features in local neighborhoods of an image, specifically properties that provide evidence for the existence of a barcode in that neighborhood. For the Hotbars finder, those properties represent the extent to which a local neighborhood appears to contain parallel lines.

Once neighborhoods are evaluated for the likelihood of containing a barcode, a clustering algorithm joins likely neighborhoods into more complete regions. These regions are further analyzed and filtered to produce the final set to be subjected to decode attempts.

The time budget for the Hotbars finder is just a few nanoseconds per source image pixel on a relatively inexpensive DSP. With meticulous hand-coding of instructions and sophisticated control of memory we can execute the Hotbars finder in a mere handful of processor clocks per source pixel. High reliability results from examining every pixel using methods that follow the image analysis guidelines noted above.

Hotbars Signal Extraction

Once regions are identified that are likely to contain barcodes, decode attempts can be made. Here, the fundamental image analysis operation is the extraction of a 1-D digital signal from the 2-D source image along a line of given orientation, often called a *projection line*. All other aspects of decoding involve analyzing these 1-D signals and so are not image analysis operations.

1-D signal extraction has a long history in machine vision, with a substantial variety of established methods. Four useful criteria for evaluating such methods can be stated as follows:

- *Geometric accuracy* refers to the extent to which the 1-D signal faithfully preserves the geometry of features in the image, which for barcodes means the relative spacing of bars and spaces and is clearly important for reliable decoding.
- *Resolution* refers to the ability to reproduce, with reasonable fidelity, features of small size along the projection line, in our case individual bars and spaces. In part, resolution depends on the spacing of the samples of the 1-D signal, with smaller spacing required for higher resolution. However, resolution can be limited by artifacts of image formation, particularly blur caused by motion or imperfect focus. Resolution can be further limited by blur introduced during 1-D signal extraction.

- *Noise reduction* refers to the ability to reduce 1-D signal noise by taking advantage of the redundancy inherent in linear barcodes, generally by signal averaging along a bar or space.
- *Speed* refers to the rate at which 1-D signals can be extracted, or equivalently the time needed to do so, as a function of the length of the signal required.

In order to better understand these criteria and the breakthrough performance that Hotbars signal extraction provides, it is useful to describe briefly a few conventional methods.

In the simplest case where the projection line lies along the horizontal, vertical or diagonal orientations of the pixel grid, 1-D signal extraction can be accomplished by copying the pixel values along these special directions, as shown in Figure 1. Because the spacing of pixels in these directions is uniform, high geometric accuracy is achieved. No additional blurring is introduced by the copying, so resolution is limited only by image formation and the one-pixel spacing of the samples of the 1-D signal (or 1.4 pixel spacing in diagonal directions). There is no noise reduction, because no signal averaging is performed. Copying is computationally trivial and therefore potentially very fast, although the limiting factor is memory speed and it is much slower for non-horizontal lines.

To provide some noise reduction, the simple example of Figure 1 can be augmented by averaging pixels perpendicular to the projection line, as shown in Figure 2. Geometric accuracy and resolution are not affected by signal averaging in this example, and speed is somewhat lower due primarily to the need to fetch additional pixels from memory.

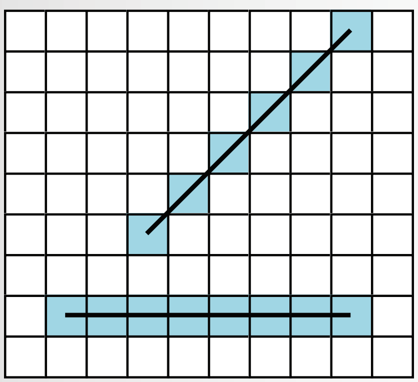

Figure 1. Pixel grid with simple horizontal and diagonal projection lines, showing pixels that will be copied

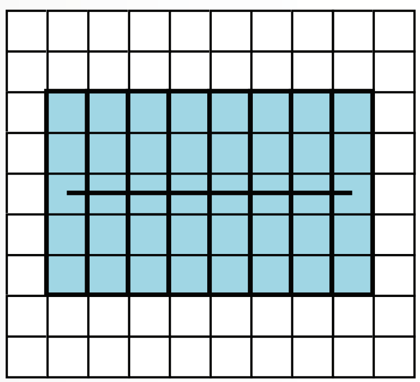

Figure 2. Horizontal projection line with signal averaging five pixels perpendicular to the line

The examples of Figures 1 and 2 provide some familiarity with the basic concepts of 1-D signal extraction, but they are not all that useful for barcode reading because projection lines cannot in general be restricted to horizontal, vertical, and diagonal orientations. At other orientations the pixel grid is far less cooperative, and so more sophisticated techniques are required. One such method that has been used for decades, and is still in use in some barcode readers, is called Bresenham line following, named after its inventor and originally used for drawing lines for computer graphics. The method makes one-pixel steps along rows, columns or diagonals in such a manner that the pixels visited lie approximately along the projection line, as shown in the example of Figure 3.

The principal advantage of Bresenham line following is that it is computationally simple and therefore potentially very fast, although again memory speed is the limiting factor. Geometric accuracy is poor, however, because the horizontal, vertical, and diagonal steps each travel a different distance along the projection line, resulting in a 1-D signal that does not accurately preserve the relative spacing of bars and spaces. No blurring is introduced, so resolution is limited only by image formation and the spacing along the projection line of the chosen pixels. There is also no noise reduction.

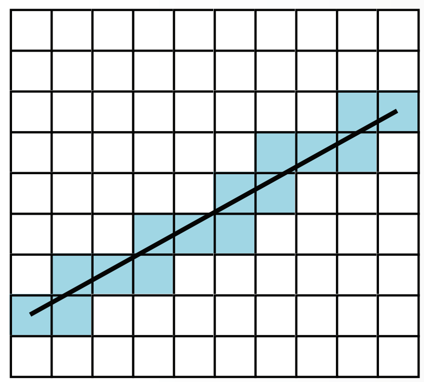

Figure 3. Example of Bresenham line following

In order to provide high geometric accuracy, good noise reduction, and acceptable resolution, contemporary state-of-the-art methods effectively rotate a portion of the image so that the projection line becomes horizontal, which allows the simple method of Figure 2 to be used. Methods for rotating a digital image are well known and typically use some form of interpolation to estimate pixel values at points in between squares of the pixel grid. The two most popular forms of interpolation are *bilinear* and *bicubic*.

Interpolation methods offer essentially perfect geometric accuracy—errors are much smaller than the size of a pixel and can be ignored. Noise reduction is also excellent, as one can use as much signal averaging perpendicular to the projection as is suitable for a given application. The principal drawbacks are resolution and speed.

Interpolation methods allow one to choose any desired spacing for the samples of the 1-D signal. By reducing the spacing below one pixel it might seem that resolution can be improved, but this is not the case because interpolation necessarily introduces blur, which is the limiting factor in resolving small features. Indeed interpolation introduces significant blur even at one pixel spacing, and so the resolution of interpolation methods is generally not as good as Bresenham line following.

Interpolation is also comparatively expensive to compute, and so interpolation methods are relatively slow. Bicubic interpolation offers somewhat better resolution than bilinear, due to less blurring, but it is much slower and therefore rarely used. Before Hotbars, bilinear interpolation was the generally preferred, state-of-the-art method because it achieves an acceptable balance of geometric accuracy, resolution, noise reduction, and speed.

Figure 4a shows a barcode imaged at a resolution of 1.5 pixels per module or PPM (a module is the smallest bar or space) and a projection line (red) along which a 1-D signal is to be extracted for a decode attempt. Figure 4b shows the 1-D signal that results from use of bilinear interpolation. All of the bars and spaces present in the 2-D image have been faithfully reproduced, and a successful decode is assured. Figure 5a shows the same barcode, but imaged at a resolution of 1.2 PPM. This lower resolution allows for a wider field of view to be captured, but as can be seen in Figure 5b, the 1-D signal resulting from bilinear interpolation cannot resolve many of the finer features. Six bars and spaces, shown with blue circles, are severely attenuated, and three, shown with yellow circles, are completely lost. The 1-D signal at 1.2 PPM cannot be decoded using bilinear interpolation. But is there sufficient information in the image to allow for the extraction of a high fidelity 1-D signal by any means?

Figure 6 shows a 1-D signal extracted from the same 1.2 PPM image, along the same projection line, but using Hotbars analysis instead of bilinear interpolation. As can be seen, there are no severely attenuated or lost features, and so the signal can be decoded. Hotbars has the same essentially perfect geometric accuracy as any interpolation method, and achieves good noise reduction, but it introduces substantially less blur.

Figure 4a. Barcode at 1.5 PPM, with projection line

Figure 5a. Barcode at 1.2 PPM, with projection line

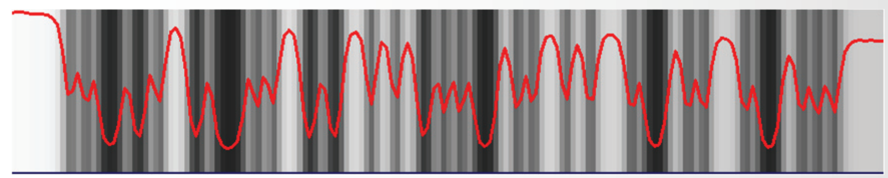

Figure 4b. 1-D signal extracted from 1.5 PPM barcode using bilinear interpolation

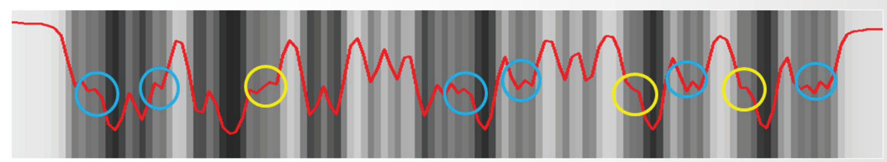

Figure 5b. 1-D signal extracted from 1.2 PPM barcode using bilinear interpolation, showing severely attenuated features in blue and completely lost features in yellow

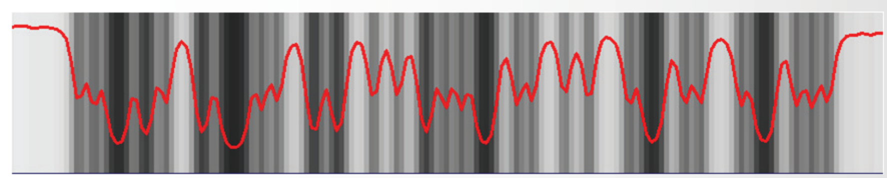

Figure 6. 1-D signal extracted from 1.2 PPM barcode using Hotbars, showing no loss of features

Interpolation methods are based on a model of rotation in the continuous plane, but a discrete pixel grid cannot accurately represent rotation at the small scales characteristic of fine features, and the result is some blurring of the signal. Hotbars has as its mathematical foundation a model of the behavior of the pixel grid itself, which allows blur to be reduced while maintaining perfect accuracy and good noise reduction. The spectacular difference between Figures 5b and 6 is due entirely to the method used for processing the source image. The information necessary to reproduce the bars and spaces is preserved in the image, even at this low resolution, but only Hotbars is able to extract it.

Generally, sophisticated analysis such as is exemplified by Hotbars comes at a price, and in machine vision that price is almost always speed. So how much does Hotbars analysis cost? Speed, of course, depends on many factors unrelated to the method in use, such as processor speed, hardware acceleration, and programming skill. For the above examples, running on a relatively inexpensive DSP, bilinear interpolation requires around 200 µs to extract the signal. For Hotbars, the time is approximately 10 µs. Rather than paying a speed price for the higher resolution, Hotbars runs about 20 times faster!

Hotbars' enormous signal extraction speed comes from using a novel and extremely efficient algorithm that is well-matched to contemporary DSP architecture. The novelty and efficiency are found in both the computation itself and in the way that memory is accessed, making Hotbars signal extraction much faster than even the simplest prior methods.

A summary and comparison of Hotbars and other commonly used methods is shown in Table 1.

Method	Omni-Directional	Geometric Accuracy	Resolution	Noise Reduction	Speed
Copy rows & columns	no	perfect	good	none	good
Rows & columns w/averaging	no	perfect	good	good	fair
Bresenham line following	yes	poor	good	none	good
Interpolation	yes	perfect	fair	good	poor
Hotbars	yes	perfect	best	good	very high

Table 1. Summary of common methods for 1-D signal extraction

Hotbars in Use

Hotbars technology is not a barcode reader, it is an image analysis foundation on which to build one. The enormous speed advantage of the Hotbars finder and signal extraction completely alters the engineering tradeoffs made by more conventional systems. When finding barcodes and extracting 1-D signals was substantially slower, one had to employ numerous shortcuts in the decoding strategy to achieve speed targets. These shortcuts, however, can lead to failure modes, which in turn lead to lower read rates. As a consequence, decoding algorithms must be carefully designed to balance speed of operation and read rates. The balance that could be achieved with conventional methods was quite satisfactory for many industrial applications, but is not competitive with high-end laser scanners in demanding, high speed applications often seen in logistics, pharmaceutical, and food and beverage industries.

Hotbars technology improves barcode readers

- Higher read rates
- More decodes per second
- Wider field of view

Hotbars has allowed Cognex to design a high-performance image-based barcode reader from the ground up. The new reader finds and decodes much faster, so the system can keep up with the high presentation rates that have until now been beyond the capability of 2-D image-based readers. Just as important, the ability to extract many more 1-D signals every millisecond has been used to eliminate decoding shortcuts, thereby reducing failure modes and improving read rates. Because the extracted signals are of generally higher fidelity, the ability to decode under-resolved barcodes is also improved, which can be used to support a wider field of view by allowing objects to be imaged at reduced resolution.

When Hotbars is combined with advances in image formation including high-intensity LEDs, liquid lenses and megapixel sensors, the result is a mature barcode reader that delivers the promise of solid-state, digital technology while not yielding performance to opto-mechanical laser scanners.

About the Author

Bill Silver, Senior Vice President & Senior Fellow, Cognex Corporation

Bill Silver is one of the most prolific and influential inventors in the thirty-year history of industrial machine vision. He studied machine vision and robotics at MIT's Artificial Intelligence Lab, earning a master's degree in Electrical Engineering and Computer Science in 1980. In 1981, he left the Ph.D. program at MIT to join the founding team of Cognex Corporation, where he created technologies that have had a profound effect on the direction of the entire industry. His work on optical character recognition, normalized correlation and geometric pattern matching have become benchmarks for industrial part identification, alignment and guidance. His most recent work has been the creation of Cognex Hotbars™ technology.

Mr. Silver holds 44 U.S. and foreign patents, with 31 additional patents pending. He received the Automated Imaging Association's Technology Achievement Award in 1994, and was nominated for the *Design News* Engineer of the Year award in 1996. In 2005 he received the North American SEMI Award with Cognex cofounder and Chairman Dr. Robert Shillman and cofounder Marilyn Matz in recognition of their significant contributions to the automation of semiconductor manufacturing.

He has served on the editorial review boards of *Photonics Spectra* and *Vision Systems Design*. In 2002, Mr. Silver was a principal witness in one of the most significant patent trials in recent history, which overturned the controversial Lemelson machine vision patents. He currently serves as the only Senior Fellow at Cognex Corporation.

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Corporate Headquarters   One Vision Drive Natick, MA Tel: +1 508 650 3000 Fax: +1 508 650 3344

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United States, West	+1 650 969 8412
United States, South	+1 615 844 6158
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