Line scan cameras for industrial image processing

Practical uses in industry and research

Line scan cameras are semiconductor cameras used in many industrial environments that often have only one photosensitive linear array. A line camera can be used for one-dimensional measurements, such as determing the width of a gap, or can produce a two-dimensional image by moving the camera or the object, like a fax machine or copier. The main advantages of a line camera include high optical resolution and speed, the ability to synchronize each line and the freedom to produce an image of almost any length. In industrial image processing, line cameras have diverse uses but their ability to make continuous recordings predestines their multiple implementation around a conveyor belt or object translation system. The output of image data for computer analysis can be via any of the modern digital user interfaces, including Gigabit Ethernet, USB 2.0 (3.0 is being implemented), CameraLink® and LVDS.

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A prerequisite for successful industrial image processing and automatic image analysis is the availability of a high quality image recording that is in focus, exhibits high contrast and is highly detailed. High image quality can only be achieved with the appropriate combination of line scan camera, high resolution lens, appropriate lighting and a precise motor unit, whether rotary or linear drive or a conveyer belt.

The image produced by a line scan camera represents the brightness profile of the test object captured by the line sensor. A two-dimensional image is also possible, by performing a scanning movement of either the test object or the camera, during which the individual line signals are transferred to the computer and assembled to produce a composite 2D image. For an image to be correct in all proportions, the scanning speed and the image acquisition process must be highly synchronized and this is most easily achieved by adjusting the transport speed to the line frequency of the camera. However, in practice, it is usually the transport speed and the image resolution that are constraining and these predefine the line frequency and ultimate choice of line camera.

At constant transport speeds, such as when examining objects on a conveyor belt, a line scan camera can be allowed to operate in a free-running mode. Conversely, any velocity fluctuations or discordant movements require the coordinated triggering of the line camera over consistent increments of travelled distance. The most convenient solution is for the software control unit of the transport motor to be made responsible for coordinating the individual line scans also. This precise synchronization guarantees images with a reproducible resolution and correct aspect ratio (see Figure 1). The line frequency f_L can be calculated for a given object speed v_0 and field width FOV, sensor length S and pixel width w from

$$f_L = \frac{v_0 \cdot S}{w \cdot FOV} \tag{1}$$

Optical Resolution

The native resolution of an optical line scan camera is defined by the number of pixels – the row of photosensitive elements in the sensor line. Line scan cameras are available with as many as 12 000 pixels. The resolution of the scanner system is determined by the objective lens chosen and the scale of the image β', as a function of the ratio of image size to object size:

$$\beta' = -\frac{S}{FOV} \tag{2}$$

$$p' = \frac{w}{-\beta'} \tag{3}$$

Also, to maintain the correct aspect ratio for an image, the pixel resolution p', (3) in the

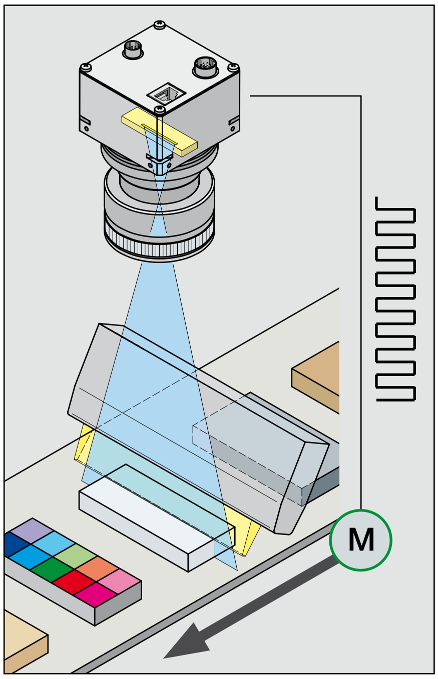

FIG 1: **The production of a 2D image requires precise synchronization of the line camera sensor and the speed of transport of the object.**

direction of the sensor (X-)axis must be identical to that in the direction of the transport (Y-)axis, perpendicular to the sensor. The resolution in the direction of transport is a function of transport speed and the line frequency of the camera as seen in Equation (1).

An identical resolution in both the X and Y axis directions is an absolute prerequisite for the geometrical measurement of the surface characteristics of the test object.

The optical resolution of the scanner system is often reported in dots per unit length, usually dots per inch or dpi.

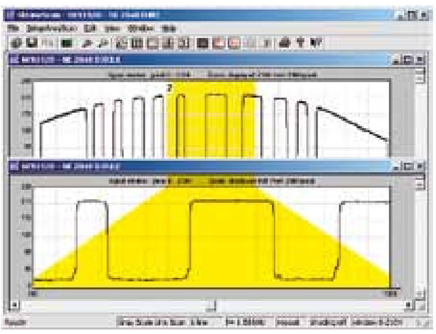

FIG. 3: **The oscilloscopic display of the line scan camera signal produced by the SkLineScan program is ideal for adjusting the camera and lens.**

FIG. 2: **Line scan cameras for industry and research: 512–12000 pixels, monochrome and color, modular interface concept.**

Exposure period and integration time

The photosensitive elements of the sensor convert the incident light into electrical charges and the duration over which the charge is accumulated is designated the integration time. These accumulated charges are shifted pixel by pixel along the sensor in a shift register to produce a read-out of the sensor. The duration of this entire process determines the exposure period.

Pixel and line frequencies

The pixel frequency is the speed with which the charges from the shift register of the sensor can be read out. The maximum pixel frequency is sensor dependent and is a function of the line pixel number (plus the sensor-dependent fixed number of passive pixels) and the minimum exposure period – the minimum time required to unload the accumulated charges. The maximum line frequency of the camera is simply the reciprocal of this minimum exposure period. Cameras with an integration control function are capable of shortening the integration time for charge accumulation within a particular exposure period (acting rather like an integrated shutter mechanism).

Interfaces for digital line scan cameras

Digital line scan cameras convert the accumulated voltages in the exposed sensor line into a digital signal with a depth resolution of 8, 10 or 12 bits. This digital data stream is transmitted via the particular interface to the computer for storage and further processing.

GigE Vision™ represents the latest interface standard for industrial image processing. A major advantage is that GigE line scan cameras can use standard network components (Gigabit Ethernet) and do not require an additional grabber board. Cable lengths of up to 100 m are possible.

With this new technology and a careful selection of the sensors, Schäfter+Kirchhoff have been able to develop line scan cameras with a Gigabit Ethernet interface that attain pixel frequencies of 120 MHz. These elevated line frequencies now make it possible to contemplate applications for GigE cameras in industry and research that were previously the provenance of dreams.

The latest generation of line scan cameras include a choice of monochrome, color or TDI (Figure 2).

Line scan cameras with a CameraLink® interface also require a grabber board in the computer to receive the signal data and are provided for seamless incorporation into already existing CameraLink® projects.

Cameras with a USB interface are more appropriate for mobile applications and tasks, especially where computers in various localities are involved in the measurement process or where the measuring instruments or experiments are controlled from a notebook computer.

Software

The SkLineScan operating program allows the line camera system to be set up without delay. The oscilloscope display of the line scan signal is a rapidly updated profile of the brightness detected by the sensor line and is perfect for adjusting the line camera and lens parameters in real-time (Fig. 3). A two-dimensional image can be obtained either in a free-running mode or by externally synchronizing the rate of image data accumulation with the transport speed of the imaged object.

The individual programming of line cameras and the development of custom application programs is explicitly encouraged.

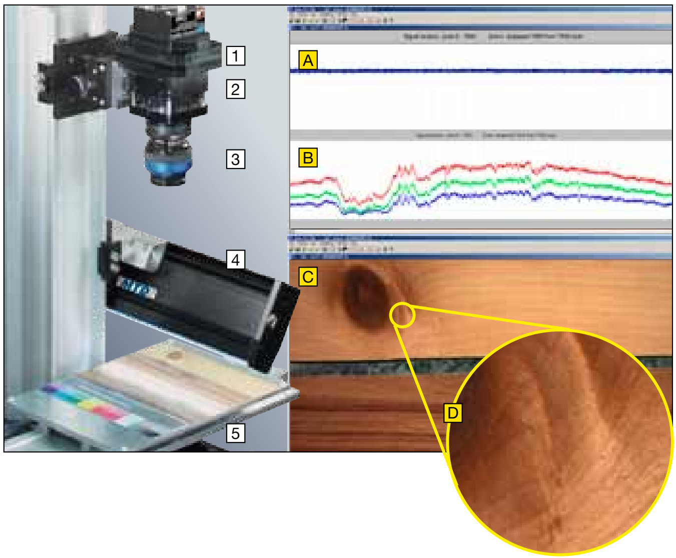

FIG. 4: Surface inspection of wood using the SK22800GJRC-XC
A: Line signal after white balance, identical RGB signal intensities
B: Line signal from brown wood surface (low blue component)
C: Area scan of the wood panel D: Zoomed section of C
1: Line camera SK22800GJRC-XC
2: Modular focus adapter FA26-S55
3: Inspection lens .x L5.6/105 b-0.33
4: LED line source MTD LED CP 300
5: Lateral translation unit SK8030-21-J

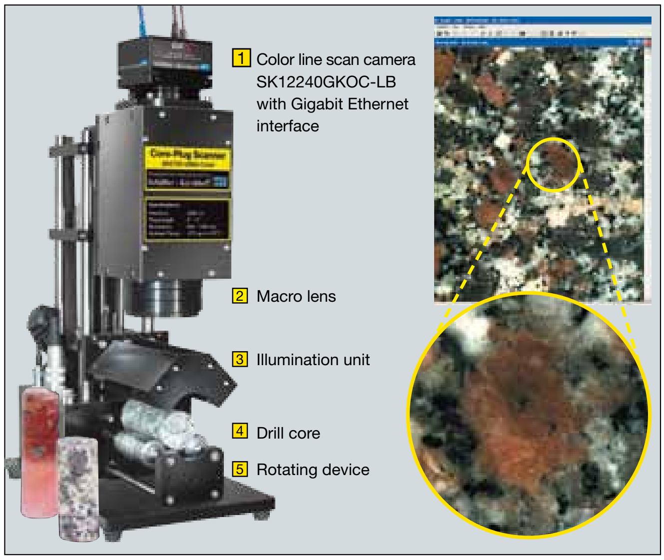

FIG. 5: The Drill Core Scanner is a line camera-based mobile imaging system developed for the inspection of geological bore plugs or drill cores. The instrument is highly robust and allows measurements to be performed directly on site.

Schäfter+Kirchhoff supply not only the SDKs, including C++ API class libraries and DLLs, for the line scan cameras with a GigE, USB 2.0 or LVDS interface but also some sample programs in C/C++ that can serve as a template for the development of personally customized applications. Source code comments and a manual complete the camera programming environment.
The development of user programs for line scan cameras with a CameraLink® interface is best performed using the SDK supplied by the particular grabber board manufacturer.

Color line scan cameras

The sensors in color line scan cameras detect the red, green, and blue (RGB) components of the signal in color-sensitive pixels. Triple line sensors have three separate sensor lines, one for each color, and with lengths up to 7600 pixels can achieve particularly high resolutions. The major determinant for attaining this high resolution is the precise synchronization of the lines for the different colors and their correct assignment in pixel mapping. When these conditions are not met then color convergence artefacts arise. The pixel width of a line scan camera sensor can range from 14 µm to 4 µm and the line spacing between the individual sensor arrays can be as much as 9-times greater than the pixel size. When the velocity of the test object is inappropriate then color convergence errors arise and become increasingly worse for sensor lines that are spaced further apart.
In contrast, the individual sensor lines of the SK22800GJRC-XC line camera (3×7600 pixels) have an intervening distance of only 9.3 µm, which is identical to the pixel size. Parallel sensor lines such as these, which are only separated by the width of a pixel, are largely immune to color convergence errors, especially when the object is freely moving or its speed cannot be controlled.
Line scan cameras with this type of sensor are eminently suitable for monitoring the pouring of bulk particulate materials or as a finish-line camera in sports competitions.
The new SK22800GJRC-XC color line scan camera also features an elevated pixel frequency of 120 MHz and is one of the fastest GigE line scan cameras worldwide. With a line frequency of 4.9 kHz, this camera is ideal for especially demanding high resolution applications involving surface inspection, such as in the timber and printing industry. The high speed of this color line scan camera, in conjunction with a high resolution objective lens, also enables its use in numerous forms of microscopy.

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Criteria for the selection of the correct line camera

- The number of pixels and their size determine the native resolution of the line camera, with higher resolutions provided by a greater number of smaller pixels. However, a high resolution is only possible with the appropriate objective lens, as structural highlights can only be captured at the sensor if the lens can is capable of distinguishing and transmitting them.
- The line frequency of the camera and the required magnification factor of the image together determine the maximum pixel resolution in the translated direction. For a given translation speed, the production of a 2D image with the correct aspect ratio is only possible when the pixel resolution of the sensor (X-)axis and that of the transport direction (Y-)axis are identical, see Equation (1).
- Anti-blooming. Without the anti-blooming function, pixels already saturated with charge can become overexposed and excess charge spills over into neighboring pixels, causing overly bright and smeared images. Cameras with the anti-blooming function are able to remove the excess charge, restoring image quality.
- Integration control acts like a camera shutter: any charge accumulation and integration thereafter, up until the end of the exposure period, is ignored once the designated integration control time has been reached. This is also effective against overexposure at high light intensities. When integration control is absent or deactivated then the integration time defaults to the full exposure period.
- Very faint objects can still be effectively imaged using a line camera with a TDI sensor, which can achieve sensitivities 96-times higher than a comparable conventional line scan camera.
- The choice of interface determines the price-performance ratio of the particular line camera system, as cameras with either a CameraLink® or LVDS interface also need a grabber board in the computer. A GigE interface has more capabilities than a USB 2.0 interface.

Table 1 provides an overview of some of the available line scan cameras together with a selection of representative technical data.

Typ	GigE Vision	USB 2.0	Camera Link	LVDS	Pixel	Pixel size	Sensor length	Integration Control	Anti-Bloom.	Line frequency (GigE)
B/W	SK512VPD	SK512UPD	SK512CPD	SK512ZPD	512	10 µm	5.12 mm	x	x	83 kHz
B/W	SK1024VSD	SK1024USD	SK1024CSD	SK1024ZSD	1024	14 µm	14.3 mm	x	x	28 kHz
B/W	SK2048VPD-L	SK2048UPD	SK2048CPD	SK2048ZPD	2048	10 µm	20.5 mm	x	x	23 kHz
B/W	SK4096VFD-L		SK4096CFD		4096	10 µm	41 mm	x	x	27.8 kHz
B/W	SK7500VTO-XL	SK7500UTO-XL	SK7500CTO-XL	SK7500ZTO-XL	7500	7 µm	52.5 mm	x		5.2 kHz
B/W	SK8160VKO-LB		SK8160CKO-LB		8160	5 µm	40.8 mm	x	x	7.15 kHz
TDi	SK2048VTDI-L		SK2048CTDI	SK2048ZTDI	2048 x 96	13 µm	26.6 mm	x	x	54.4 kHz
TDi	SK4096VTDI-XL		SK4096CTDI	SK4096ZTDI	4096 x 96	13 µm	53.2 mm	x	x	14 kHz
	SK12240VKOC-XL		SK12240CKOC-XL	SK12240ZKOC-XL	3 x 4080	10 µm	40.8 mm	x	x	4.8 kHz
	SK22800VJRC-XC		SK22800CJRC-XC		3 x 7600	9.3 µm	70.9 mm	x		4.9 kHz

TABLE 1: **Technical data for selected digital line cameras using different interfaces. Although the different cameras in each row have identical sensors, the maximum line frequency of each camera is determined by the interface used. Representative line frequency data is given for the GigE version.**

A long line color camera for the wood and printing industry – an application example

The exemplary system in Figure 4 consists of the SK22800GJRC-XC color line scan camera with a GigE interface and a high resolution lens, a linear sliding transport mechanism and an LED line light; all controlled by appropriate coordination and imaging software.

The particular LED lighting is chosen for its excellent homogeneity over the entire image field. The predefined lighting profiles are coordinated with the imaging profiles of the color line scan camera and uploaded using the camera Ethernet interface. The LED performance is optimized for the different surfaces and textures to be expected from wood samples of various types.

This particular measuring width of 224 mm produces a resolution of 30 µm per pixel (850 dpi) and achieves a scan speed of 15 cm.s^{-1}. At the other extreme of coverage and speed, an image of a measured width of 3 m at a resolution of 64 dpi can be performed at a scanning speed of 1.9 m.s^{-1}.

Drill core scanner

The drill core scanner is a portable surface scan macroscope for investigating cylindrical test objects and was specifically designed for the on-site inspection of drill cores.

The scanner components include a color line scan camera with GigE interface (optionally USB 2.0), a lens, an LED lighting unit, a motor unit with rotary drive and a compilation of comprehensive software for the coordinated control of the motor, lighting and camera (Figure 5). The drill core is rotated using a dual roller system under the control of the software, which also triggers successive acquisitions of a line image by the camera, at predetermined intervals of angular velocity of the rotated core sample.

The resolution of up to 2040 dpi enables the mineralogical composition of the bore plugs to be investigated and any traces of precious metals or valuable resources, such as gold or oil, can be flagged for further analysis.

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