Introduction to Line Scan Cameras

Fundamentals:
Function and Applications 8
Setting up a Line Scan Camera System 12
Choosing the right Camera Interface 14
What are Line Scan Cameras?

Line scan cameras are semiconductor cameras used in many industrial environments. The single photosensitive line sensor contains – depending on type – up to 22800 picture elements (pixels). Light energy incident on the sensor is transformed into an electric signal for digitization within the camera.

At 8-bit resolution, the A/D converter transmits the output voltage of each pixel into one of 256 brightness levels, at 12-bit resolution into 4096 brightness levels.

Color line scan cameras provide three separate line signals for Red, Green and Blue with either 3 x 8-bit or 3 x 12-bit per pixel. The digitized output signal is transferred to a computer via various interfaces according to requirements, e.g. Gigabit Ethernet or USB 3.0.

The advantages of a line scan camera include

- high optical resolution of up to 8160 pixels (monochrome) or 3 x 7600 pixels (color RGB)
- high speed of up to 54 kHz line frequency
- flexible parameter setting for the line scans
- synchronizing of each individual line, as well as the triggering of frames
- when focused on the zenith of cylindrical objects, the line scan camera delivers sharp, distortion-free images of the external surface during rotation
- flexible image height from 1 up to 64000 lines per image
- continuous scanning of endless materials such as foils or paper without a time limit.

Creating an image

The image produced by a line scan camera is one-dimensional and represents the brightness profile of an object, captured at the current position of the line sensor. A two-dimensional image is generated by performing a scanning movement of either the object or the camera, during which the individual line signals are transferred to the computer and assembled one by one into a 2D image.

The line frequency $f_L$ can be calculated for a given object speed $v_o$ and field width $FOV$, sensor length $S$ and pixel width $w$ from

$$f_L = \frac{v_o \cdot S}{w \cdot FOV} \quad (1)$$

Improving the image

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 conveyor belt. 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. Where there are velocity fluctuations or discordant movements then external triggering of the line scan camera is required. The trigger pulses, e.g. from an encoder, are equidistant and independent of the movement velocity so that the camera will be triggered after a constant travelled distance.

This precise synchronization guarantees images with a reproducible resolution and correct aspect ratio.
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 more than 8000 pixels. The resolution of the scanner system is determined by the objective lens chosen and the scale of the image $\beta'$, as a function of the ratio of image size ($FOV$, field of view) to object size $S$:

$$\beta' = \frac{S}{FOV} \quad (2)$$

$$p' = \frac{w}{-\beta'} \quad (3)$$

Also, to maintain the correct aspect ratio for an image, the pixel resolution $p'$, (3) in the 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 determined in Equation (1).

An identical resolution in both the X and Y-axis directions is an absolute prerequisite for the accurate 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.

### Camera Application:

1-dimensional
- Signal generation: individual line scan
- Examples: measurement of width, rod diameter, edge positions, glass thickness.

2-dimensional
- Several line scans are combined to produce a 2D image (frame)
- Examples: surface inspection, endless webbing inspection, texture analysis, scanning.

### Line Scan Camera Applications

Generally, the applications can be grouped into one-dimensional or two-dimensional measuring tasks.

For one-dimensional applications, the measured result is extracted from the pixel information of an individual line scan. Measurements of two-dimensional images require moving either the object or the line sensor.

**Camera Application:**

1-dimensional
- Signal generation: individual line scan
- Examples: measurement of width, rod diameter, edge positions, glass thickness.

2-dimensional
- Several line scans are combined to produce a 2D image (frame)
- Examples: surface inspection, endless webbing inspection, texture analysis, scanning.

### 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 more than 8000 pixels. The resolution of the scanner system is determined by the objective lens chosen and the scale of the image $\beta'$, as a function of the ratio of image size ($FOV$, field of view) to object size $S$:

$$\beta' = \frac{S}{FOV} \quad (2)$$

$$p' = \frac{w}{-\beta'} \quad (3)$$

Also, to maintain the correct aspect ratio for an image, the pixel resolution $p'$, (3) in the 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 determined in Equation (1).

An identical resolution in both the X and Y-axis directions is an absolute prerequisite for the accurate 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.
Synchronization of line scan cameras

In practice, a line scan camera has to be externally synchronized in order to obtain distortion-free images, e.g. triggered by an encoder.

There are two different synchronization functions that can be applied together or individually:

1. Line synchronization:
   A TTL signal at the LINE SYNC input triggers each individual exposure of the sensor line by line.

2. Frame synchronization:
   The recording of a set of lines (frame) representing a two-dimensional image is triggered by a TTL signal at the FRAME SYNC input.

Line Synchronization Modes:

FreeRun / SK Mode 0
The acquisition of each line is synchronized internally (free-running) and the next scan is started automatically after completion of the previous line scan. The line frequency is determined by the programmed value.

LineStart / SK Mode 1
After an external trigger pulse, the currently exposed line is read out at the next internal line clock. The start and duration of the exposure are controlled internally by the camera and are not affected by the trigger pulse. The exposure time is programmable. The line frequency is determined by the frequency of the trigger signal.

Limitations: The period of the trigger signal must be longer than the exposure time used. Between the external trigger signal and the internally generated line clock, jitter occurs in the range of the exposure time.

ExposureStart / SK Mode 4
(only available when the camera supports integration control)
A new exposure is started exactly at the point in time of the external trigger pulse. The exposure time is determined by the programmed value. The exposed line is read out after the exposure time has elapsed. The frequency of the trigger signal determines the line frequency.

Limitation: The period duration of the trigger signal must be longer than the exposure time used.

ExposureActive / SK extSOS (Mode 5)
The exposure time and the line frequency are controlled by the external trigger signal. This affects both the start of a new exposure (Start of Scan-Pulse, SOS) and the readout of the previously exposed line.

Frame Synchronization
The camera suppresses the data transfer until a falling edge of a TTL signal occurs at the FRAME SYNC input. This starts the acquisition of a 2D area scan. The number of image lines must be programmed in advance. Any of the available line synchronization modes can be used for the individual line scans.

Timing: FRAME SYNC + LineStart
Shading correction and white balance

All lenses show some vignetting as a function of the field angle. Hence, even with homogeneous object illumination, the signal intensity of the image decreases with increasing image height.

Shading correction (or flat field compensation) is used to compensate for lens vignetting as well as for inhomogeneity in the illumination. Shading correction is achieved by performing a white balance calibration during illumination of a homogeneous white target.

An individual gain for each pixel is obtained by scaling each value to a normalized maximum signal. The oscilloscope display now shows a homogeneous intensity distribution along the entire length of the line sensor.

The shading correction procedure is also used for white balance calibrations in color line scan cameras. The different sensitivities of the individual color channels of the sensor are compensated for, as well as any color inhomogeneity arising from the illumination source.

The SkLineScan software package provides all necessary functions for the performance of shading correction and white balance.

For individual software needs, library functions for shading correction and white balance are provided in the SDKs for the various interfaces.

Sensor alignment

For linear illumination sources, rotating the line sensor results in asymmetric vignetting.

The camera and illumination optics can be aligned optimally by monitoring the object illumination using the oscilloscope display.

Shading correction and white balance

A monochrome line scan camera signal of a homogeneous white calibration target showing signal trimming caused by either lens vignetting or inhomogeneous object illumination

B Monochrome line scan camera signal after shading correction

C Signal from a color line scan camera of a homogeneous white calibration target showing the effect of trimming on red, green and blue signals

D Color line scan signal after shading correction

E Pop-up window for performing shading correction in the SkLineScan software allows white balance calibration to be performed automatically or manually

Sensor alignment

A Sensor and illumination optics rotated in apposition

B Sensor and illumination optics aligned properly
Setting up a Line Scan Camera System

Lens focusing performed using the oscilloscope display

The real-time display of the line scan camera signal facilitates the focusing of the camera lens. This display can even be used to focus a line scan camera system when making measurements in two dimensions. Variations in edge steepness at dark-bright transitions and modulations in the line scan signals provide a useful mechanism for establishing the correct focus (see figure). Initial focusing is performed with a fully opened aperture, when the depth of field is at its smallest and the sensitivity of focus adjustment is at its largest. The integration time can also be shortened to provide a sufficiently sensitive low amplitude signal.

Evaluation of a correct focus setting by using the line scan signal

- **A** Line scan camera out of focus: edges are indistinct, signal peaks are blurred with low modulation of high frequency densities
- **B** Zoom of highlighted area in **A**
- **C** Area scan with focus settings **A** and **B**
- **D** Line scan camera signal with optimal focus setting: dark-bright transitions have sharp edges, highly modulated signal peaks with high frequency density variations
- **E** Zoom of highlighted area in **D**
- **F** Area scan with focus settings **D** and **E**
Blooming – Anti-Blooming Fundamentals

Blooming and Anti-Blooming Correction

When the pixels are saturated from excessive illumination and cannot accumulate more charges, they transfer part of their charges to neighboring pixels – an effect termed blooming. Blooming leads to the corruption of the geometrical assignment of the signal and the image generated by the line sensor.

A line scan camera with an anti-blooming sensor can effectively dissipate the surplus charge resulting from over-exposure by using a ‘drain gate’. The less exposed neighboring pixels are no longer corrupted. Over-exposures of up to 30-fold can be drained successfully, depending on the pixel frequency and spectral range of the line sensor.

Line scan camera signal from a bar code using a midtone incident light and the SK2048U3JR line scan camera without an anti-blooming sensor.

1. Line signal with enhanced illumination of the central range

2. Zoom of the signal depicted in 1 showing the steep signal edge

3. Extension of the integration time by a factor of 3.81 produces edges that are no longer vertical and have noticeable shoulders – the blooming of the sensor has begun

4. Over-exposure caused by too large an integration time leads to severe signal and data corruption when using line scan cameras without anti-blooming

5. Extreme over-exposure floods the dark pixels of the sensor, the offset control is disturbed and the line scan camera produces an attenuated signal
Choosing the appropriate camera interface

Schäfter+Kirchhoff supplies more than 70 different types of line scan camera with either a Gigabit Ethernet, GigE Vision, USB3.0 or CameraLink interface. The choice of interface should be considered at an early stage of a new line scan camera project, because it determines important properties such as maximum cable length and maximum line frequency. The table below gives a detailed comparison of the available camera interfaces.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Gigabit Ethernet</th>
<th>GigE Vision™</th>
<th>USB 3.0</th>
<th>CameraLink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Cable Length</td>
<td>100 m</td>
<td>100 m</td>
<td>3 m up to 100m with fiber optical cable extension</td>
<td>10 m</td>
</tr>
<tr>
<td>Max Pixel Frequency</td>
<td>120 MHz</td>
<td>120 MHz</td>
<td>150 MHz</td>
<td>3 x 70 MHz</td>
</tr>
<tr>
<td>External Synchronization</td>
<td>Line Sync</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Frame Sync</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Sync Divider</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>—</td>
</tr>
<tr>
<td>Number of Devices</td>
<td>up to 255</td>
<td>up to 255</td>
<td>up to 127</td>
<td>up to 4</td>
</tr>
<tr>
<td>Grabber Board</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>CameraLink Frame Grabber</td>
</tr>
<tr>
<td>Required PC interface</td>
<td>GigE</td>
<td>GigE</td>
<td>USB 3.0</td>
<td></td>
</tr>
<tr>
<td>External Power Supply</td>
<td>required</td>
<td>required</td>
<td>not required</td>
<td>required</td>
</tr>
</tbody>
</table>

Available Software

- **Image Acquisition and Configuration Tools**
  - Windows: SkLineScan-GigE-WIN
  - LabView: SkGigEconfig tool
  - Linux: SkLineScan-U3-WIN

- **Software Development Kit (SDK)**
  - Windows: SK91GigE-WIN
  - LabView: —
  - Linux: Pleora SDK

Software Compatibility

- **Gen<eb>-CAM™**
  - ✔️

---

Inroduction to Line Scan Cameras
Features selection criteria

In addition to the interface, other important technical features of the cameras should be considered when selecting a camera for the required application.

Technical considerations include:
- pixel number
- pixel size
- sensor length
- maximum line rate
- anti-blooming
- integration control
- dynamic range
- spectral sensitivity

Pixel number / line rate:
A high optical resolution is obtained from a large number of pixels. However, the line rate of the chosen camera must be high enough to reach this resolution in the scanning direction at a given scanning speed.

Sensor length:
A suitable lens must be available for the specified sensor length and desired magnification.

Anti-blooming:
Blooming from the transfer of excess charges from oversaturated pixels to adjacent pixels can cause signal broadening and signal loss. Cameras with an anti-blooming function drain the charge excess and restore favorable signal characteristics.

Integration control:
Line scan frequency is inversely proportional to exposure time; while the charges from a finished line scan are read out, the next line scan is being exposed. Thus, the minimum exposure period is achieved at the maximum line scan frequency. Integration control can act as a shutter by truncating the accumulation of charges and ending the line scan period. For high light intensities, over-exposure and blooming can also be avoided using integration control.

Dynamic range and digitalization depth:
Depending on the sensor used, line scan cameras are characterized by their dynamic range (signal-to-noise ratio). Some digital line scan cameras can be operated with either 8 or 12-bit digitalization depths.

Spectral sensitivity:
The spectral sensitivity of the line scan camera must be appropriate to the wavelengths of the light source used and the optical properties of the measured object. Cameras used for laser-based measurement systems have different spectral sensitivities than a color scanning system. Because of these spectral sensitivity characteristics, a color line scan camera of the KOC series requires a UV/IR blocking filter when used in daylight.