Office Software Assesses Illumination for Linescans

There is a straightforward way to calculate lighting levels for linescan cameras with some basic formulae entered into a spreadsheet. **Mike Muehlemann** explains what to do.

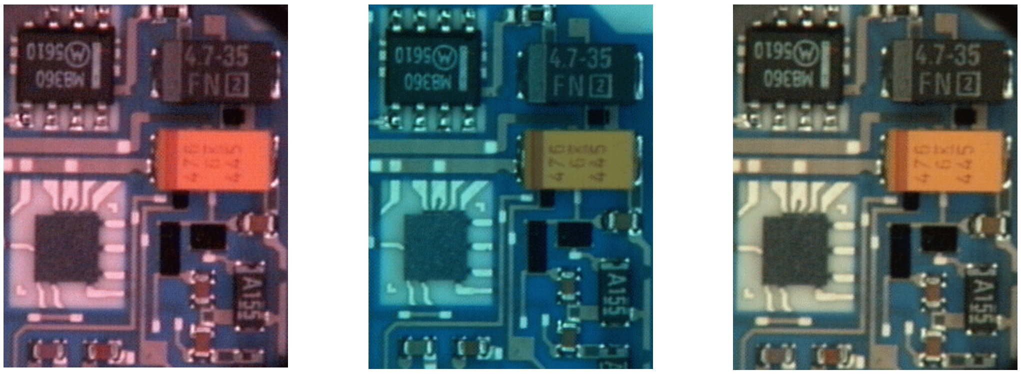

Fig 1: How a colour sensor "sees" an object lit by a tungsten halogen lamp (left) which emits a lot of red, and a mercury lamp (centre), emitting a lot of blue. Right: what it "sees" after a spreadsheet determines intensity levels to balance the signal levels from red, green and blue channels.

Veterans of machine vision know the benefits of proper, efficient illumination and the many pitfalls of improper lighting. Contrary to popular belief, lighting is not black magic and, while system design demands some creativity, illumination is based on simple physics.

Lighting's principal job in machine vision is to provide the necessary contrast to detect required features. Its basic elements, including the geometry of the linescan system plus the target's spectral, transmission and reflectance values, define the lighting intensity needed to ensure a sufficient signal from the CCD camera. The illumination must be sufficiently intense and constant, and the system structure must remain stable, for the system to be reliable.

Estimating lighting intensity for linescan applications requires more work that for area scan cameras because the integration time for a linescan is not fixed and it is not so straightforward to experiment with lighting levels. A quick analysis can produce rudimentary numbers, but these are often incorrect and misleading. Errors arise because the parameters of most lighting problems depend strongly on wavelength, and most first-order calculations assume some constant value for each parameter.

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Simple spreadsheets

An analysis results in a series of integrals over the wavelength region of interest, which tends to make the problem more difficult to solve. However, computers and spectral data from many vendors allow very accurate calculations with simple spreadsheets.

A full evaluation of a lighting system for machine vision must take the following variables into account:

- the spectral power distribution of the lightsource;
- the transmission characteristics of any illumination optics;
- the spectral reflectance values of the product under inspection;
- the modulation transfer function of the camera lens;
- the CCD sensor's spectral sensitivity;
- the required resolution of the inspection task;
- the linear speed of the product under inspection.

The first five variables are wavelength dependent, so any estimate that uses a single constant value for any of these parameters can lead to significant errors. The last two items define the acquisition rate of the camera, both of which effect the camera output because the response is directly proportional to the time during which the illumination impinges on the CCD sensor.

The best way to determine illumination levels is to work backwards. Start by determining the line rate for the camera from the required resolution for the inspection task. Calculate the horizontal resolution, which is defined as the number of pixels per the horizontal (cross-web) field of view. The word "resolution" may be misleading in this case because we will specify only one pixel per object element in the field of view (FOV).

Have at least two pixels for each minimum, detectable object element in order to resolve the smallest feature defined by the application specification. Therefore, horizontal resolution will be limited only by the number of pixels in the camera and by the number of cameras used to cover the FOV.

Vertical resolution (down-web) is defined by the velocity of the product and the line rate of the camera. Assuming that the vertical resolution is the same as the horizontal resolution, the line rate is given by

$$\textbf{Line Rate} = V/HR$$

Where V is the velocity of the web and HR is the horizontal resolution. Thus the CCD integration time, T, is given by

$$T = 1/\textbf{Line Rate}$$

Next, the responsivity curve of the sensor determines the minimum irradiance to drive it into saturation. The analogue output per wavelength of the CCD sensor is given by

$$V(\lambda) = R(\lambda) * E(\lambda) * T$$

Where $V(\lambda)$ is the analogue signal, $R(\lambda)$ is the CCD responsivity and $E(\lambda)$ is the irradiance on the sensor, each as a function of wavelength.

Therefore the sensor's analogue output is the sum of the individual products of the irradiance and responsivity multiplied by the integration period:

$$V = T * \sum_{\lambda} [\, R(\lambda) * E(\lambda) \,]$$

or for the saturation condition,

$$V_{sat} = T * \sum_{\lambda} [\, R(\lambda) * E_{sat}(\lambda) \,]$$

Where V_{sat} is the analogue saturation of the CCD sensor and E is the irradiance necessary to produce saturation. Both values are obtained from manufacturer's data.

There is no direct solution for E_{sat}, so one must adjust the amplitude of E mathematically until the value of the series reaches the saturation value. There are or course an infinite number of solutions to $E_{sat}(\lambda)$ depending on the spectral curve's shape.

Lamp choice

Not only will different lamps make big differences in $E(\lambda)$, but every element in the lighting system will modify the basic shape of the illumination spectrum as it the light travels through the system. The most notable modifying element is the product under inspection. Therefore, to make sense, any calculation must focus on the specific application; *the object under inspection*. This is a fundamental issue that is often overlooked.

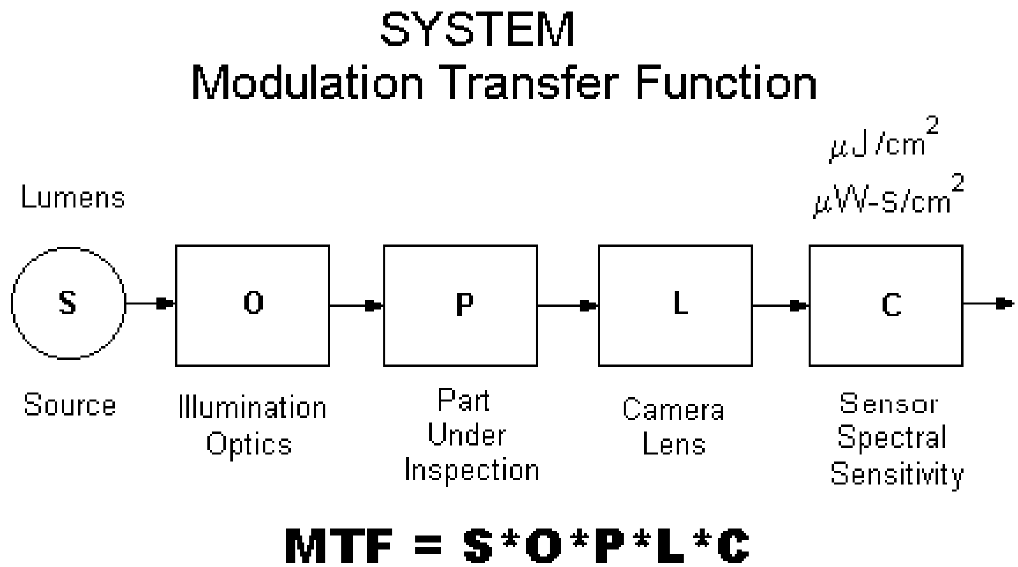

Fig 2: The modulation transfer function is the product of each element's transmission.

Once E(λ) is established, it is simple to enter the above summation formula into a spreadsheet. In theory we should be able to take the lamp's power and calculate the irradiance on the CCD sensor. The transfer function for the entire system is then the multiplication effect of the lamp collection system, the transfer function for the illumination optics, the spectral reflection of the product under inspection, the throughput of the camera lens and the spectral responsivity of the CCD sensor. Figure 2 represents this standard system in block diagram form.

It is theoretically possible to calculate E(λ) on the sensor from the associated transfer functions, but this is a daunting task. The effort to properly characterize each element is impractical, and yet anything less introduces sufficient error to make the entire exercise a waste of time.

In practice therefore, the light source is chosen first by matching the spectral output to the product under inspection, structural considerations, *anticipated* intensity requirements, lamp lifetime and overall cost; but not necessarily in that order. Once a suitable lamp technology has been selected (assuming that at least one exists), then the structural issues must be addressed. These spectral and structural considerations must provide the proper contrast ratios while reducing unwanted or artificially introduced contrast (shadows, glints, nonuniformity, secondary reflections, etc.) The last and final issue is always that of light intensity.

Rather than start the measurement process at the light source, the best approach uses a combination of theory and experiment; the measurement should be made right after the product under inspection. Here it is simple to measure the spectral radiance of the product under the illumination scheme previously defined to meet all other criteria. Once the spectral radiance of the object is known, one can calculate the effects of the lens and the spectral responsivity of the CCD sensor to determine the sensor saturation radiance.

Note that the radiance of the image is essentially the same as the radiance of the object under inspection, subject to losses in the lens.

Therefore:

$$\mathbf{R(\lambda) = S(\lambda) * T_r}$$

Where $R(\lambda)$ is the spectral radiance at the image plane, $S(\lambda)$ is the measured spectral radiance of the object under inspection and T_r is the radiance transmittance of the lens, from the manufacturer.

The irradiance at the sensor $E(\lambda)$, is then the radiance times the solid angle subtended by the lens at the sensor. This depends on the diameter of the lens and any iris to stop the lens down. The irradiance at the sensor will be

$$\mathbf{E(\lambda) = R(\lambda) \;/\; [2*f\# * (m+1)]}$$

or

$$\mathbf{E(\lambda) = [\, S(\lambda) * T_r \,] \;/\; [2*f\# * (m+1)]^2}$$

Where $S(\lambda)$ is the spectral radiance of the object (measured), T_r is the radiance transmittance of the lens, f# is the f number (focal length/diameter of the lens) and m is the magnification (image size/object size).

Maximum area

The physical size of the lens and of the aperture stop limit the maximum area or clear aperture. Thus, as either the magnification or the focal length of the lens increases, the CCD irradiance decreases as the square of the change. Because the lens magnification is usually fixed by the application, choose as fast a lens (as short a focal length) as possible and one that has a large, clear aperture. Most “off-the-shelf” lenses cannot meet both of these conditions as well as the distortion and depth-of-field requirements.

In critical cases a custom design provides a fast lens that can meet the distortion and depth-of-field requirements. Standard “off-the-shelf” lenses can increase demands on the lighting system, thereby leading to higher costs and reduced lamp lifetimes, which in turn raise the cost of maintenance.

It is now possible to calculate irradiance at the sensor, based on the measured sample radiance. From earlier,

$$\mathbf{V} = T * \sum_{\lambda} [\ \mathbf{R}(\lambda) * \mathbf{E}(\lambda)\ ]$$

or for the saturation condition,

$$\mathbf{V}_{\mathbf{sat}} = T * \sum_{\lambda} [\ \mathbf{R}(\lambda) * \mathbf{E}_{\mathbf{sat}}(\lambda)\ ]$$

and we have just determined that

$$\mathbf{E}(\lambda) = [\ \mathbf{S}(\lambda) * \mathbf{T_r}\ ]\ /\ [2*\mathbf{f\#} * (\mathbf{m}+1)]^2$$

Therefore

$$\mathbf{V} = T * \sum_{\lambda} [\ \mathbf{R}(\lambda) * \mathbf{E}(\lambda)\ ]$$

$$\mathbf{V} = T * \mathbf{T_r}\ */\ [2*\mathbf{f\#} * (\mathbf{m}+1)]^2 \sum_{\lambda} [\ \mathbf{R}(\lambda) * \mathbf{S}(\lambda)]$$

All of the constants are known. The calculation is a summation of the product of the spectral responsivity of the camera and the spectral radiance of the object. The spectral responsivity of the camera is in the manufacturer's data, and a calibrated spectrometer measures the object's spectral radiance. A simple spreadsheet can be constructed for the execution of this formula. A sample spreadsheet example of this technique is demonstrated in Figure 3.

	A	B	C	D	E	F
1						
2	λ (nm)	R(λ) V/μJ/cm²	S(λ) μW/sr-cm²	R(λ)*S(λ) (V-sec)	Input/ Output	Variables
3						
4						
5	300	$1.0x10^{-2}$	$6.0x10^{-4}$	$6.0x10^{-6}$	Line Rate(Hz)=	1400
6	310	$3.0x10^{-2}$	$8.0x10^{-4}$	$2.4x10^{-5}$	Lens Tr =	.85
7	320	$5.0x10^{-2}$	$5.0x10^{-4}$	$2.5x10^{-5}$	Lens f# =	1.4
8	330	$6.0x10^{-2}$	$9.0x10^{-4}$	$5.4x10^{-5}$	m =	0.5
9	*	*	*	*		
10	*	*	*	*	V =	=(F6*D87)/((F5*2 *F7*(F9+1)²)
11	*	*	*	*	V_{sat} =	(From Data Sheet)
*	*	*	*	*		
*	*	*	*	*		
*	*	*	*	*		
83	1080	$6.1x10^{-2}$	$2.0x10^{-3}$	$1.2x10^{-3}$		
84	1090	$5.9x10^{-2}$	$1.5x10^{-3}$	$8.9x10^{-4}$		
85	1100	$5.8x10^{-2}$	$1.3x10^{-3}$	$7.5x10^{-4}$	% of Required Intensity	=F10/F11*100
86						
87				SUM(D5:D85)		

Fig 3: Example Spreadsheet. Variables must also be inserted for the line rate, lens parameters and image magnification.

The result of interest is quickly examined in cell F85. This cell allows the user to rapidly define how much additional intensity will be required based on all the important parameters of the application. The importance of this technique over all others, is that the number generated here already takes into account the structural and spectral properties that provide sufficient contrast first – it is now just an issue of intensity. If the value in cell F85 is less than about 25%, the results tells you that you are going to have big hurdles to overcome in order to successfully implement the application as originally envisioned.

Comparative Lamp Analysis

R(λ) and S(λ) are rarely constant or even linear over the wavelength region of interest. The impact of these wavelength-dependent terms on the power of a light source needed to saturate a sensor is made clear when one examines the typical CCD spectral responsivity curve (see Figure 4). To illustrate the difference in potential output, a CCD camera may be aimed at a perfect white Lambertian target and illuminated by either a standard tungsten halogen or a fluorescent lamp.

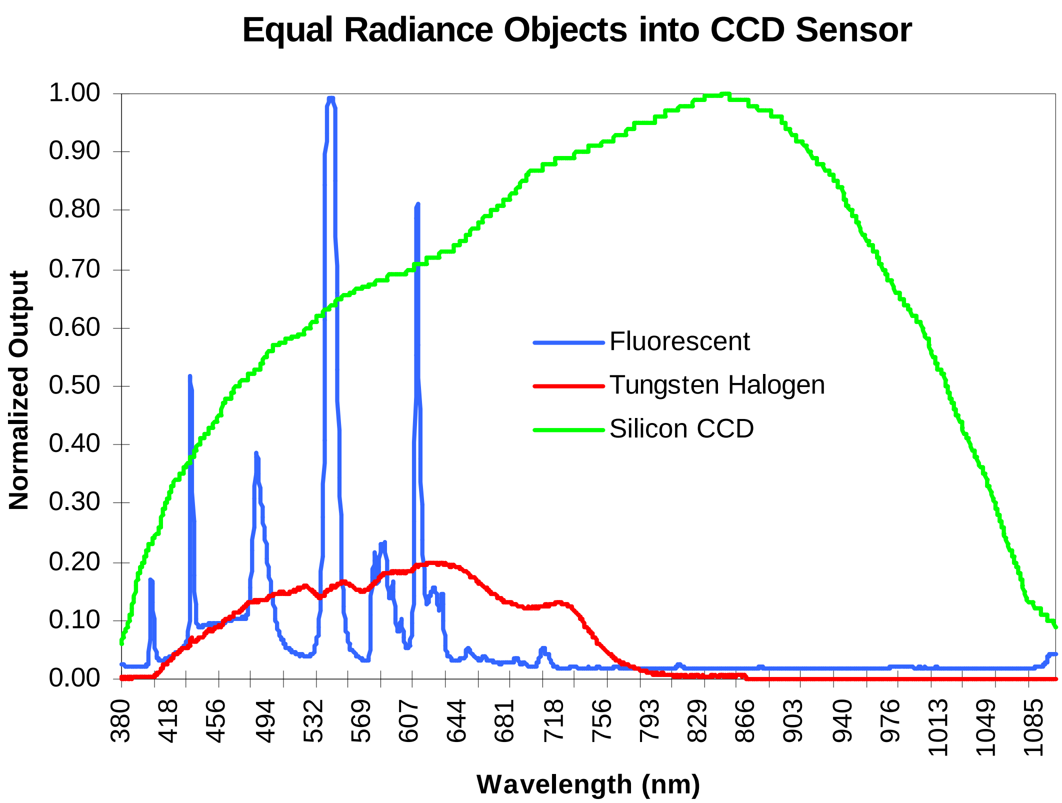

Fig 4: Emission and sensitivity spectra of the sensor and two different lamps. Even though both of these lamps have equal radiance, they ***do not*** produce the same output signal on the CCD sensor.

To mathematically demonstrate the varying outputs versus the different spectral inputs, the individual spectral radiance curves can be adjusted via scaling constants to provide equal spectral radiance values, **S**, where

$$S = k * \sum_{\lambda} S(\lambda)$$

In this sample comparison the S(λ) curves are measured by a calibrated spectrometer and adjusted in the spreadsheet by a scaling parameter, k, to ensure that both lamps provide the same total spectral radiance values.

Then these two equal spectral radiance curves are independently multiplied by the corresponding camera spectral responsivity values, at each wavelength, to generate the theoretical response of the sensor. For more accurate results, make the summation at a maximum of 10 nm intervals (1 nm recommended) to reduce the approximation error associated with a spreadsheet-type integration.

Better signal

If you perform the above experiment, you will immediately see two interesting consequences. First, the CCD sensor generates almost 20% more signal sensitivity from the tungsten halogen lamp than from the fluorescent lamp of equal radiant output. This is due to the greater sensitivity of the CCD sensor in the red part of the spectrum. Even more importantly, the power required to achieve equal levels of object radiance may be dramatically different, based on the dissimilar nature of the structure and the efficiency with which the two lamps create equal radiance at the target.

This is the driving reason for measuring illuminance after the product under inspection. Object radiance is the single biggest variable in the equation and the one with the largest spectral reflectance variation, but the efficiency with which the target is illuminated can run a close second.

The required measurements are easily made with a calibrated spectrometer, and the data can be inserted into a simple spreadsheet. Loading the spectral responsivity curve from the CCD manufacturer in the next column allows the required multiplication and summation to be easily performed. If the measurements are made in 1 nm increments, the resulting figure can be multiplied by the remaining constants to determine the percentage of necessary illumination that has been measured. It is then a simple task to determine the optimum illumination level for the application.

This relatively simple process can be performed with amazing accuracy. The basic physics is easily understood and the spreadsheet solution is simple to set up and implement. The procedure is based on a strong balance between theoretical methods and experimental measurements.

There are still issues with respect to the structure, cost and lamp technologies that will always have to be addressed. However, once they have been resolved, it is straightforward to determine the intensity levels required for successful implementation – or not. ♦♦♦

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