Finding the perfect lighting solution for line-scan applications

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1. Preface

Successful applications of vision systems are dependent on the following components: camera, lens and illumination. This document deals with the task to find the best light solution for line-scan applications. It illustrates the basics of different illumination technologies and demonstrates how cost-effective rework can be avoided by choosing the appropriate light solution.

Acquiring images of moving targets is a challenge and consequently the best image requires three fundamentals to be well defined:

- an excellent camera
- an appropriate lens
- an appropriate illumination

All three items are the key to enable subsequent successful image analysis, while poor image quality will task any machine vision application.

The illumination choice is the first step that directly affects the quality of the images. There are many difficulties resulting from the wrong illumination selection. In general what is not illuminated correctly cannot be evaluated by software or even by humans. A camera can also not be compared to the human eye which adapts automatically and is very flexible to difficult tasks. A human would even change the distance or the angle of view to discover details. So for a machine vision camera it is not possible to detect edges if the object is not illuminated correctly. A lot of experience is needed to choose the right illumination for a new application or material. The effort in making the right selection are often underestimated and lead to avoidable difficulties which can increase the costs of a project or even worst cause it to fail.

In today’s vision applications different tasks have to be solved. Metallic shiny, matt dark or even transparent surfaces with different features require different types of illumination which lead to the development of different illumination technologies. A lot of aspects affect the choice of the correct illumination and have to be allowed for:

- area to be illuminated
- camera in use
- speed of the application and the camera itself
- color of the illuminated objects
- environment
- behavior and characteristics of the object (glossy, diffuse, height variations,…)
- expected / required lifetime of the application

If all of these parameters are understood, the application can be simulated and it can be determined which illumination fits best. All the mentioned parameters and topics that have to be observed make it understandable why light is so important. Unfortunately in many cases a simulation of the total setup is not available and that way the selection of the right illumination is still a challenge.

2. Brightness: Can an application really have enough light?

Many people are not aware of what are the ingredients for a good machine vision application. In line-scan applications the light should be where the sensor array(s) of the camera are focused. Light outside this area is wasted of and results in extra costs and heat.

In all imaging technologies, one important quality criteria is noise. There are several sources of noise in an imaging system but normally, the shot noise dominates.

Shot noise is caused by a physical effect and has nothing to do with camera quality. The reason for shot noise is founded in the discrete nature of the light (photons) and the resulting discrete generation of electrons in a sensor pixel.

Shot noise has a Poisson distribution and therefore, the signal to noise ration can be described as

$$SNR = \sqrt{N_e} \qquad \textbf{(Eq. 1)}$$

The number of electrons N_e is direct proportional to the number of photons.

The number of photons is direct proportional to the product of sensor illuminance E_V and exposure time.

In a given imaging setup with a defined optical transformation there are three parameters that influence the shot noise in an image

- integration time (⬄ scanning speed)
- f-stop (⬄ depth of focus and maximum sharpness)
- illuminance on the scanned object

The f-stop of a lens has a significant impact on the requirements for light. Changing the f-stop from e.g. 4 to 5.6 increases the light requirement by a factor of two if trying to keep the same signal-to-noise ratio. At the same time it increases the depth of focus and improves the optical quality with most lenses. So the depth of focus and sharpness increase while vignetting effects are reduced. What machine vision application wouldn't benefit from having a sharper image and an increased depth of field?

<u>Example:</u>

Object resolution:	300 DPI
Sensor pixel size:	10 µm
Focal length:	50 mm

⇨	Depth of focus:	8 mm	// f-stop 4.0
⇨	Depth of focus:	12 mm	// f-stop 5.6
⇨	Depth of focus:	18 mm	// f-stop 8.0

General hints:

- Increase the f-stop number and increase the illumination so that images are sharper while not reducing the signal to-noise ratio.

- Increase the brightness to a range where the camera reaches 80% (or more) of the sensor saturation when scanning the brightest area of an object.
- Shot noise is one of the most important parameters for image quality. So collecting as many photons as possible within the defined integration time will increase image quality.

These conditions in image acquisition reduce risks, increase quality and reduce the processing power in PCs that are required to overcome problems during the imaging processing.

The speed of line-scan cameras has increased significantly during the last years and it is becoming more and more of a challenge providing enough light for these fast systems. Anyone with a digital camera already realizes that poor light conditions lead to poor (noisy) images. The same happens in machine vision applications. So the challenge is to produce enough light for these difficult applications. The importance of light for camera applications is shown by effects of shot noise. Image quality is strongly correlated with the number of photons on the object and finally the sensor used for acquisition. Modern line scan cameras are able to deal with integration times down to e.g. 15 µs, a luminance of more than 1 Million Lux can be required to produce optimum image quality. The two images show signal to noise problems which are caused by lack of light.

Image 1:Small SNR

Image 2: High SNR

Image 1: Signal to noise ratio (SNR) of two images

The following chart shows a typical setup with SNR related to illuminance.

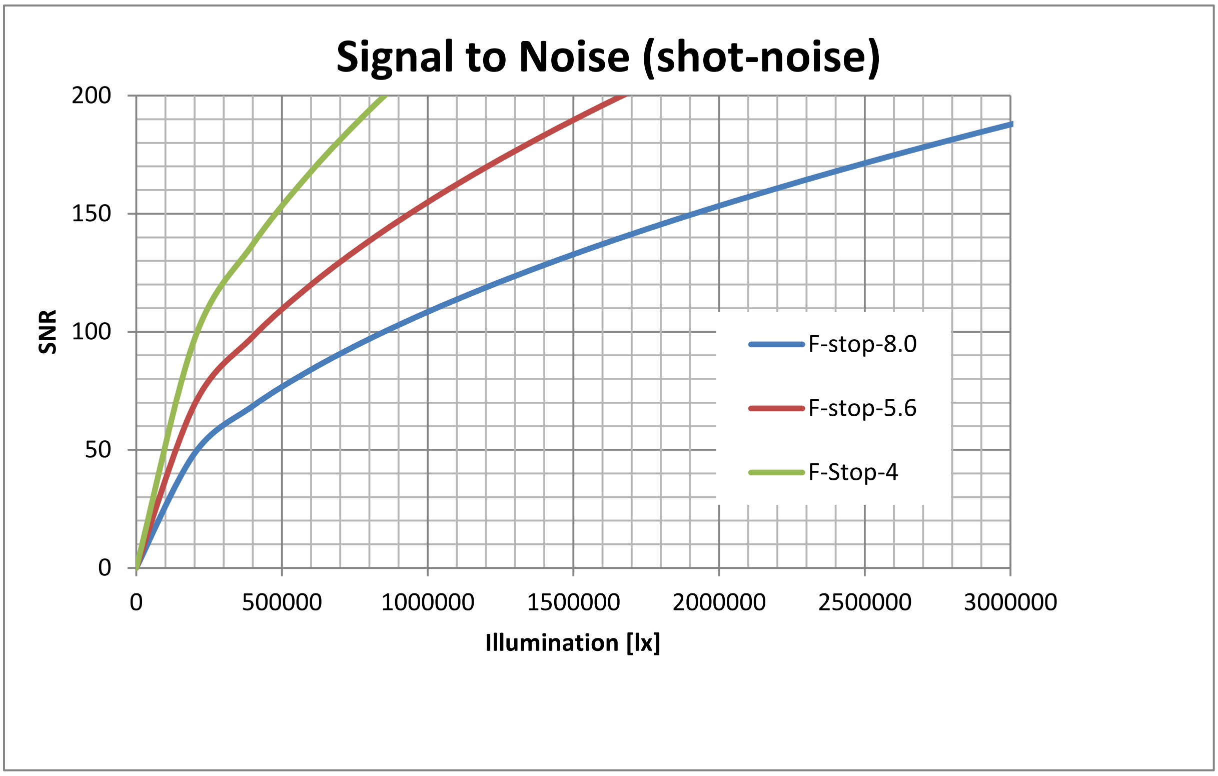


Image 1: Example of SNR resulting from shot noise // 20 µs integration time, 200 DPI resolution, diffuse reflection with 80%

Some lighting systems on the market provide focused light solutions to increase intensity at the point of imaging. When it is not a backlight or bright field illumination it is a challenge generating enough light on the object so that line-scan cameras can provide perfect images. This is why rod lenses are commonly used to focus light.

Chromasens holds a unique patent for reflector technology in line-scan applications. While rod lenses cause color aberrations resulting from diffraction effects, a mirror (reflector) principle is free of such issues. With reflector technology it is also feasible collecting more light (wider angle) of an LED and that way efficiency is typically higher.

3. Lifetime and degradation

Illumination technology today is constantly changing from classic lights like halogen or fluorescence bulb lamps to LED based lights. The success of the LED is driven by a lot of advantages and industrial improvements. Classical light sources (e.g. halogen bulbs) change spectrally and take a long time to reach a stable state. Additionally these have a very limited lifetime. The spectral behavior of LEDs is stable when the temperature and current are held constant and the LED light sources are ready for operation almost immediately.

The short time for warm up is because of the small size. This is one reason why good thermal management is needed to keep the LEDs at a reasonable working point. The recent improvement in the stability of LEDs enables a long lifetime and a constant quality of spectral behavior. There are different options to increase the lifetime by adequate thermal management and also by controlling the operation mode of LED illumination. This means e.g. if LED illumination is strobed, which is technically easy to implement, the lifetime will increase. With strobing technology it is partially possible to use the LEDs over the maximum current for tasks where intense light is required. But be aware that latest high-power LEDs do not support excessive currents as before.

The natural behavior of an LED over the lifetime is that the intensity will decrease. Measurements showed that in 50.000h the intensity decreases from 100% to 70%. During that time the LED performance will show a gradual reduction.

4. *Temperature: Cooling is important*

Is LED light really a cool light source? If LEDs are driven hard without cooling, they burn out and die within seconds – if there is no adequate cooling. Cooling is an issue and the better the cooling the longer the lifetime of the LED. This is now common knowledge but there are other adverse effects to consider.

LED temperature influences:

- Lifetime
  Spectral behavior / color shift (see table 1)
- Efficiency / brightness

The following table illustrates the color shift caused by a change in LED temperature. The listed values are the mean and maximum color distances in Lab space, measured on a Color Checker test chart and referenced on the 55 °C-Values.

Temperature	Mean ΔE (to Ref 55°C)	Max ΔE (to Ref 55°C)
60°C	1	2,2
65°C	1,7	3,6
70°C	2,8	5,9
80°C	4,1	8,2
90°C	6,1	12,4

Table 2: Spectral changes of an LED over temperature, 55°C as reference

As it can be seen in the table spectrum changes due to temperature variation as shown in the table below. 30°C difference can have an influence on the spectral behavior from 2,2 to 12,4 ΔE (delta E).

Remark: ΔE>1 will result already in visible color changes.

In applications where precise color reproduction is essential, it is strongly recommended to guarantee the thermal management of the illumination.

Active thermal control systems can control the LED's temperature by intelligent cooling in a narrow range of less than 2 degrees.

In general the following cooling options are available. Corona II supports all options.

- passive cooling by heat sink
- compressed air cooling
- liquid cooling
- fan cooling
- temperature controlled fan cooling

Active air flow, compressed air and water cooling are best for measurement applications in high temperature environments. By monitoring the temperature of the LEDs and controlling the cooling (e.g. fan-based) ΔE issues can be avoided. Cooling helps to minimize the color shift of the LEDs and leads to more accurate measurements. It also helps to increase the lifetime of the light.

5. *The challenge of different working distances*

If an engineer has an application where the object is flat and the working distance is known then there are fewer issues to solve. The selection of the focal length can be relatively easy in this case. But what to do with varying distances because the object does not have a well defined distance to the light?

Reflector technology enables a greater usable depth with an illumination source. The images show the advantage of the reflector technology in regard to the distance.

Homogeneity is needed over the length, width and depth. The following image shows a reflector focus of 190mm.

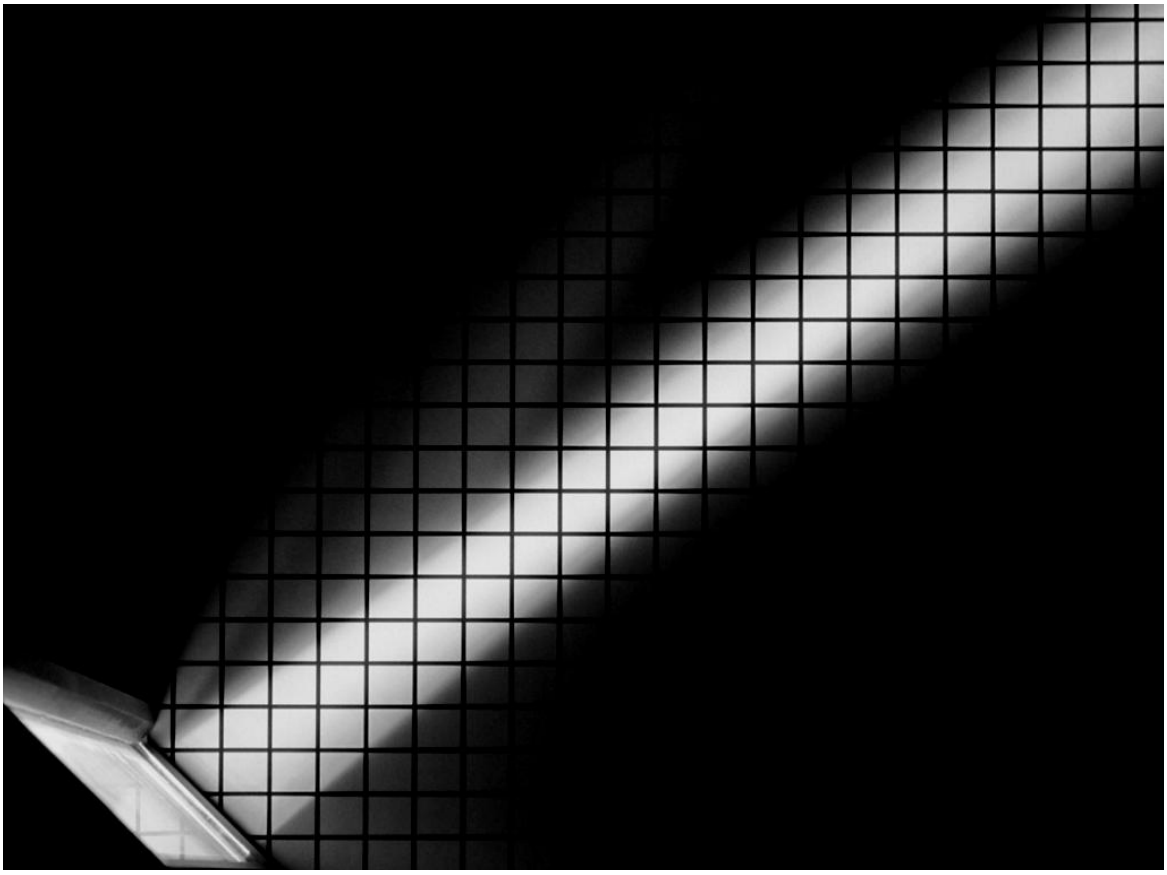


Image 4: Corona II focus 190mm

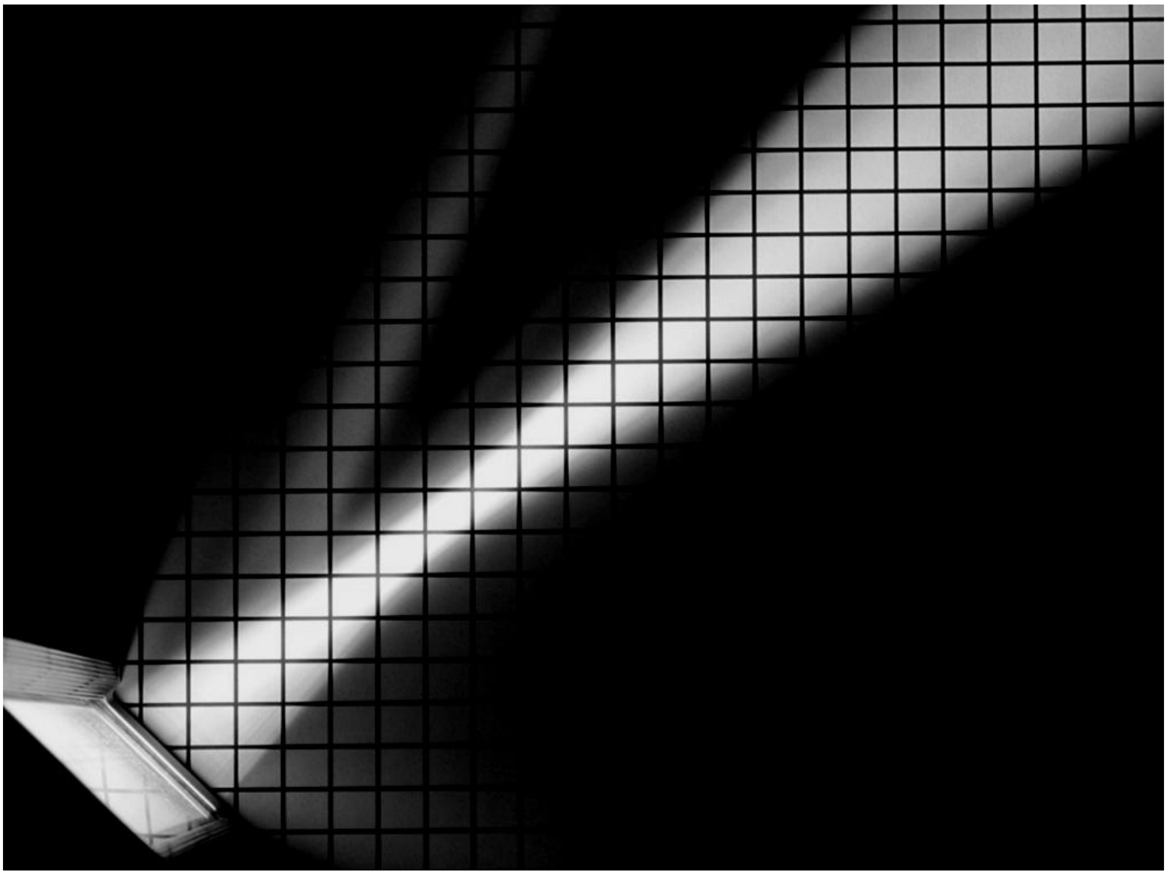


Image 5: Corona II focus 95mm

With white LEDs spectral issues are commonly caused by chromatic lens errors.

The CORONA II illumination focuses the emitted LED-light via a special and patented reflector technology. Focusing by reflector technology does not lead to chromatic aberrations which can be a challenging issue in applications with white light and varying distances. A focused light with no aberrations even with different angles and distances increases the efficiency and stability in applications.

If an object has varying distances to the camera/light varying brightness is an additional challenge for a subsequent image processing task. So a careful selection of a light source that has minimal changes in brightness even with varying distances is highly recommended.

Image 6 shows on y-axis the relative brightness with varying distances.

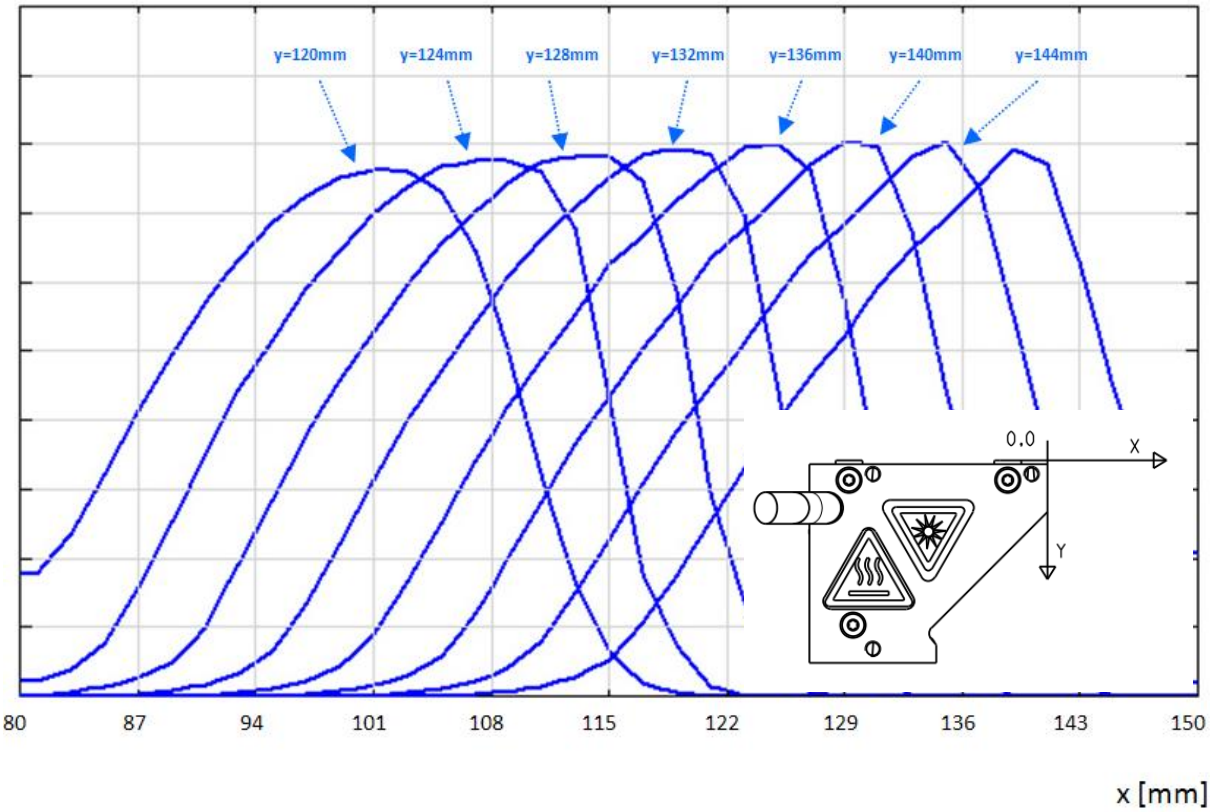


Image 6: Typical illumination profile for a Corona II reflector Type C (Focal Length 190mm)

6. *Choosing the right illumination length*

Every lens causes a decrease in brightness resulting in raw images when viewing angles are further from the center towards the edges. The decrease of brightness is proportional with $\cos^4$ (*phi*) where *phi* is the angle measured from the optical axis.

As it can be seen in **image 7** there is a significant brightness decrease from the center to the outer regions of an image. So there are good reasons not to have wide viewing angles as the brightness and accordingly the SNR will decrease from center to the edges.

Additionally the right length of a light is important for any application to avoid additional problems at the outer regions of images. While the center of an object receives energy from both sides, the outer edges of an object will suffer a lack of light.

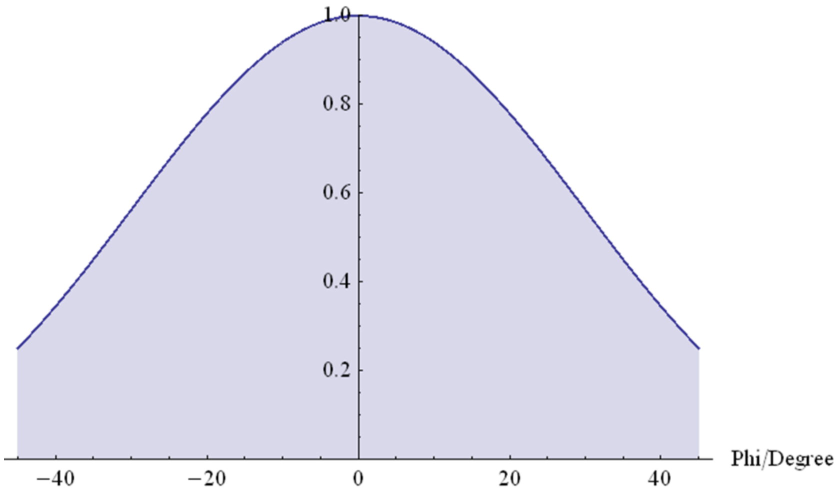


Image 7: $\cos^4$(Phi) related brightness decrease

It is recommended to have illumination modules that are longer than the object itself. The larger the distance between the illumination and object, the longer the unit should be.

To have ample light conditions the following rule of thumb can be used:

IL = FOV + 2*D **(Eq. 2)**

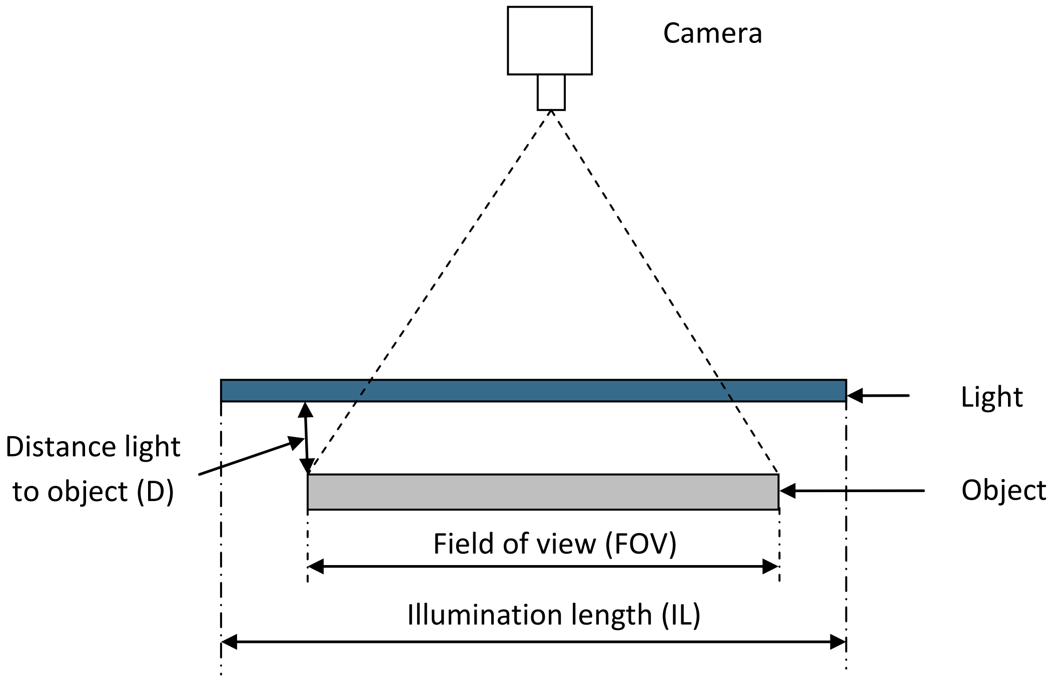


Image 8: Illumination length vs. distance to the object

7. *White LEDs: The right selection*

LEDs are available in many different colors like red, green, blue, yellow, amber, white, IR. UV LEDs are also available, but with wavelengths smaller than 365 nm the lifetime is very short and emissions are weak. On the other hand IR- LEDs with wavelengths greater than 950 nm have a very limited output. Nevertheless different colors and wavelengths help to make things visible on surfaces with different spectral behaviors.

In the past red illumination was often used where high intensities were required. Latest performance boosts in LED technologies are mainly in white LEDs. We see these high-power LEDs in headlights of cars or even street lamps. The core of a white LED is in fact a blue LED. And it is the phosphors that convert part of the blue to the remaining visible spectrum.

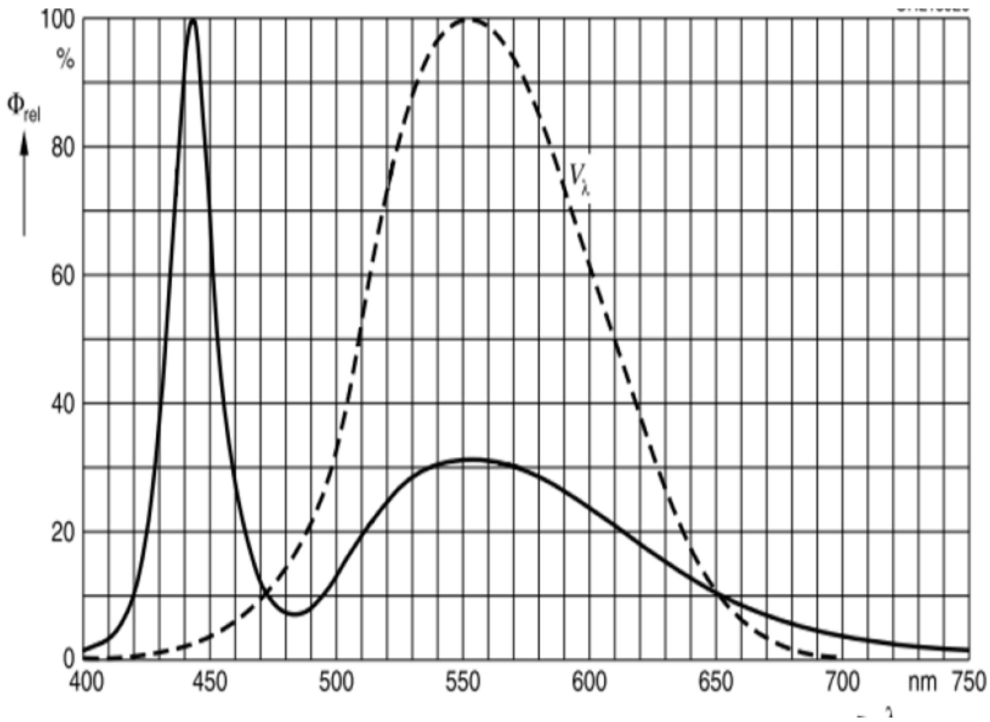


Image 9: Spectral emission of a typical white LED.
The dotted line shows the spectral sensitivity of a human eye

Image 9 shows the blue peak near 440 nm of the blue LED inside a white LED. The remaining part of the spectrum results from the conversion material (phosphors). Technology wise it is a challenge for LED manufacturers keep the color of white LEDs stable. There are tolerances in the blue chip and additional tolerances in the conversion material. This all leads to unwanted different white colors produced within the same production line. That way LED manufacturers classify LEDs into different groups. Each group (binning) has a certain tolerance range with respect to efficiency and color.

In terms of selecting the right illumination source, the binning should be considered. If the illumination modules differ in color from piece to piece or even inside the same illumination unit, it will complicate the image analysis.

8. Non-visible spectra, where to use?

UV LEDs are used to make fluorescence marks visible. In many cases 405nm light sources are sufficient to excite fluorescent substances. On the other hand for curing processes of glue, varnish or resin, UV LEDs may be the better choice. UV LEDs are not as powerful – compared to blue/white LEDs, but the intensity can be increased by focusing the UV beams via reflector technology.

IR lights are used in food inspection applications to detect organic materials. Wavelengths of 1200-1700nm can help to distinguish between different materials. Unfortunately today's IR LEDs in these wavelength ranges are not yet powerful enough, so conventional halogen bulbs with filters are used.

9. Polarization

Reflecting materials or surfaces are always a challenge with respect to illumination. In combination with a 90 degree rotated polarizer in front of the camera, unwanted light reflections can be eliminated.

Without polarizer

With polarizer

Image 10: Images with and without polarizer

Polarization in technical applications is a challenge. On one hand it is key that the illumination module will stay within certain temperature ranges, on the other hand a crossed polarizer arrangement cuts down the efficiency to approx. 18% of the initial emission. So with respect to a good SNR (signal-to-noise ratio) the primary emission needs to be very high, enabling acquisition of good images even with the crossed polarizer arrangement.

10. LED controllers: What are the key parameters?

There are different concepts on the market. Some controllers are integrated, and others are external, and sometimes now even used. A LED controller is not just a different kind of power supply. It can be the key to success.

A stable inspection unit requires a stable environment. If the LED controller is not stable in terms of temperature variations or supply current to the LEDs, brightness changes can make material inspection impossible. Especially with the very high frequencies of line-scan cameras special care is required with the selection of the LED controller. Short-term fluctuations in brightness will immediately be visible.

In industrial environments a robust design and the right choice of interfaces must be available. Control interfaces allow adjusting the light output remotely e.g. different materials need to be inspected on the same production line but require different light levels.

Available interfaces are

- Ethernet
- RS485
- USB
- RS232
- PWM
- Analog

If controllers are designed for special light systems – as it is with the pairing of the XLC4 and the Corona II – a monitoring /surveillance function can also be integrated. An inspection system can read e.g. from the combination XLC4/Corona II the LED and controller temperature as well as other useful information. This enables stability analysis and control in a machine vision application.

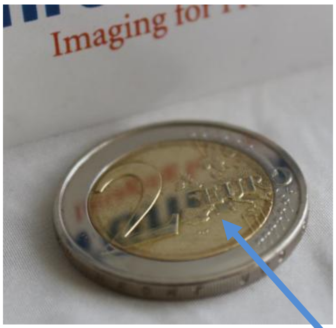
11. Conclusion

Material inspection with vision systems is a challenging task. A lot of different aspects need to be taken into account. A profound knowledge of potential side-effects is critical.

Light is the basic essence for vision systems. A careful selection of the light source minimizes risks and is the key to success.

12. *Appendix: Different Illumination situations on a coin*

The following images show the influence of different illumination technologies on the same object. It shows the difficulty to choose the appropriate technology.



Detailed view with different illumination arrangements

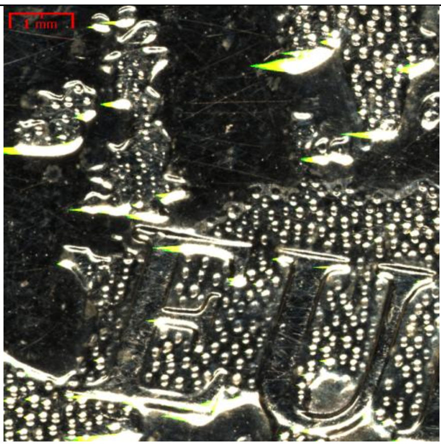
Dark Field Illumination	**Dark Field Illumination with diffuser**
	
Bright Field Illumination	**Bright Field Illumination with diffuser**
	
Bright Field Illumination and polarization	**Dome Light Illumination**

Image 11: Same object different illumination