White Paper

High Dynamic Range Imaging: Images and Sensors

Fundamentals, Method of Functioning, Application

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1 Introduction

In the past, technological development in the image sensor field primarily strove to increase resolution by adding pixels. The current generation of digital cameras already offer resolutions over 10 Megapixels. This allows details too small to be seen with the human eye to be imaged, provided the optics are up to the task.

With regard to dynamic range, however, human sight is far superior to conventional image capturing devices. If a scene contains very bright and very dark areas, a camera will quickly reach its limits. While the eye can perceive all brightness levels, image sensors suffer from overexposure and therefore lose image data.

HDR (High Dynamic Range) technology, on the other hand, enables fine differences in brightness to be imaged even in very bright scenes, similar to the human eye. This white paper explains the background behind HDR technology and the method of functioning of HDR image sensors. It will focus specifically on the new *FX4* HDR sensor, which was presented by IDS in the *uEye* camera series in 2009. Finally, potential uses and limits of the new technology will be identified.

2 The fundamentals

The abbreviation HDR (sometimes seen as HDRI) stands for *High Dynamic Range (Imaging* or *Imager)* and refers to the capture or generation of digital images with a high dynamic range. Images captured using conventional means, on the contrary, are designated as LDR, or *Low Dynamic Range*.

2.1 Definition of dynamic range

The dynamic range (also known as contrast) of an image refers to the ratio of the largest brightness value to the smallest brightness value. In other words, a scene has a high dynamic range if it contains both very light areas and very dark areas at the same time (example: an image of a person with their back to the sun). A scene may also exhibit great brightness with minimal dynamic range because there are no dark areas (example: looking directly at the sun).

2.1.1 Measuring dynamic range

Dynamic ranges are usually specified in the logarithmic unit dB (decibels). The dB value expresses the factor by which the highest brightness value is greater than the lowest brightness value. The ratio of two brightness values, l_1 and l_2, can be converted into a value D in dB with the following equation:

$$D = 20 \cdot \lg\left(\frac{l_1}{l_2}\right) dB$$

A typical image sensor with a dynamic range of 60 dB could image a scene dynamic of 1,000:1, i.e. the highest brightness value is 1,000 times brighter than the lowest brightness value. The human eye can perceive a dynamic range of up to 100 dB within a scene, which corresponds to a brightness ratio of 100,000:1. The following table shows the corresponding dynamic range for different values in dB.

Value in dB	Dynamic range
60	1,000:1
80	10,000:1
100	100,000:1
120	1,000,000:1

Table 1: Values for dynamic range in dB

2.2 Characteristics and image capture

When perceiving or imaging a scene, the form of the imaging characteristic is crucial for displaying the differences in brightness. With image processing (e.g. applications such as edge detection and character recognition), linear characteristics are generally required. The human eye, on the other hand, perceives differences in brightness based on a logarithmic characteristic, which often approximates a gamma characteristic in practice. All three forms will be shown in the following.

2.2.1 Linear characteristic

If a system (e.g. a camera with a conventional CCD sensor) yields double the output value for double the brightness, the system features a linear characteristic (*Fig. 1*).

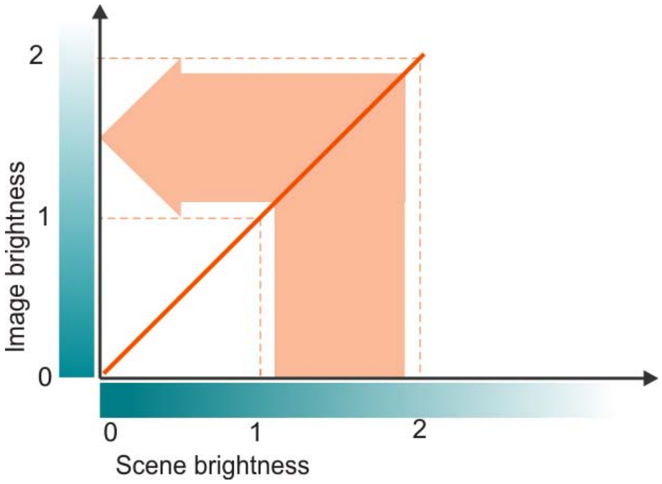

Fig. 1: Imaging with linear characteristic

2.2.2 Gamma characteristic

Gamma characteristics (or gamma curves) are named after the Greek formula symbol γ. Gamma curves are power functions of the form

$$y = x^{\frac{1}{\gamma}}$$

and are often used in photography or image display on computer screens. A gamma value of 1 generates a linear characteristic again. A curve with the value $\gamma = 2.2$ used for computer screens is shown in *Fig. 2.*

Such a gamma characteristic brightens dark areas of an image (see *Fig. 3*), which corresponds more to the perception of the human eye. In light areas of an image, the differences in brightness are condensed for this.

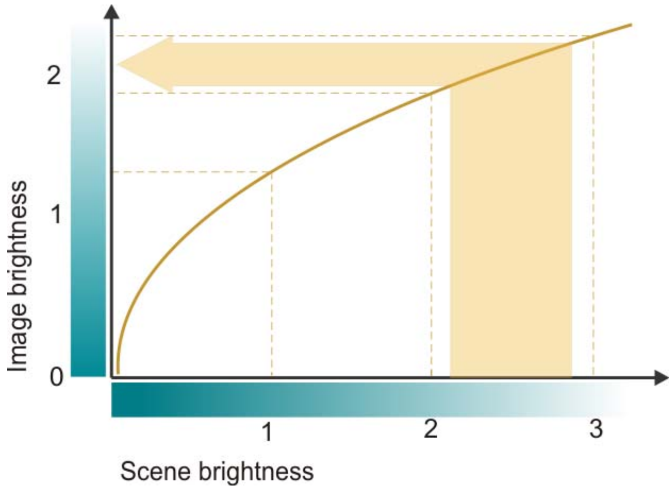

Fig. 2: Imaging with gamma characteristic

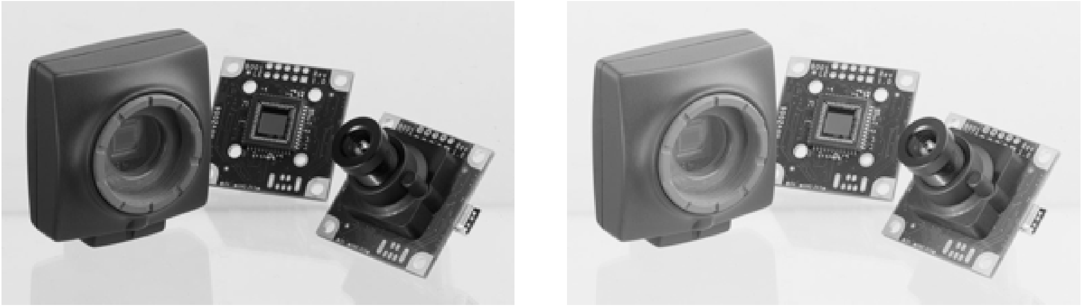

Fig. 3: Image with linear characteristic (left) and gamma characteristic (right)

2.2.3 Logarithmic characteristic

The effect of the logarithmic characteristic is even stronger. Here, the characteristic follows the function

$$y = \lg(x)$$

The diagram in *Fig. 4* illustrates how very large jumps in brightness in light areas of a scene only cause small changes in image brightness. This explains why image sensors with a logarithmic characteristic, in particular, are ideal for imaging scenes with very high dynamic range.

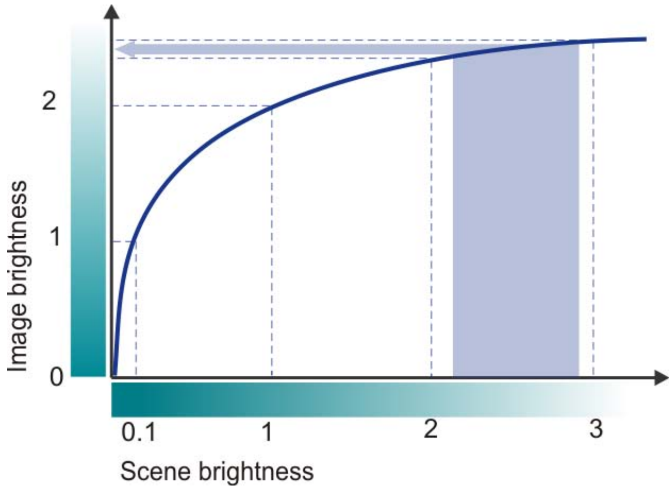

Fig. 4: Imaging with logarithmic characteristic

2.3 Dynamic range with digital images

When digitizing images, it must be ensured that the dynamic range of the captured image can be displayed correctly in the selected image format. The bit depth with which the images were digitized is decisive here.

2.3.1 Bit depth

Image sensor pixels first generate an analog voltage signal proportional to the amount of light that strikes them. The image is digitized for further processing, i.e. the stepless signal is converted to a digital numerical value. The following *Fig. 5* shows this using a gray gradient as an example. If the stepless gradient is imaged in a digital range in 2 bits, for example, the result is $2^2 = 4$ levels; for 4 bits, it is $2^4 = 16$ levels, and so on. The intermediate brightness values of the original gradient are irreversibly lost after digitization.

With around 200 levels or more, the jumps in brightness can no longer be discerned with the eye, which is why current monitors and digital cameras use 8 bits (256 levels) per color channel (fully adequate for visualization).

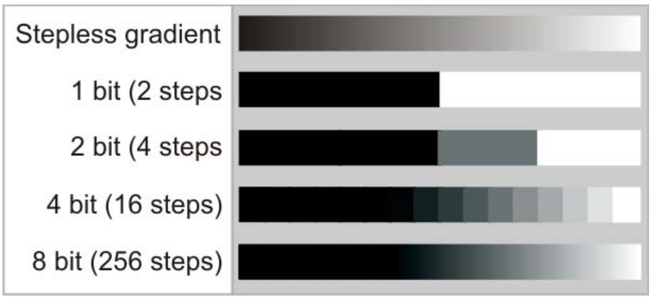

Fig. 5: Various bit depths using a gray-scale gradient as an example

2.3.2 Greater bit depth in image processing

If digital image data undergoes further image processing, a bit depth greater than 8 may be necessary. The computer is able to differentiate between these very fine differences in brightness (no longer discernable by the eye) and process them. This is why industrial cameras often use 12 bits.

Bit depth	Brightness levels
8	$2^8 = 256$
10	$2^{10} = 1{,}024$
12	$2^{12} = 4{,}096$
14	$2^{14} = 16{,}384$

Table 2: Bit depth and corresponding possible brightness levels

Greater bit depths require extremely low-noise image sensors, however. As soon as the differences in brightness created by noise are greater than the digitization levels, no further data is gained.

2.3.3 Histogram and digital contrast adjustment

The brightness distribution of digital images is represented in a histogram[1]. If an image has optimum contrast, the histogram includes practically all brightness values between 0 and the highest value (255 in 8-bit images). If an image has low contrast, the histogram only includes a small number of the values; the image appears dull *(Fig. 6).*

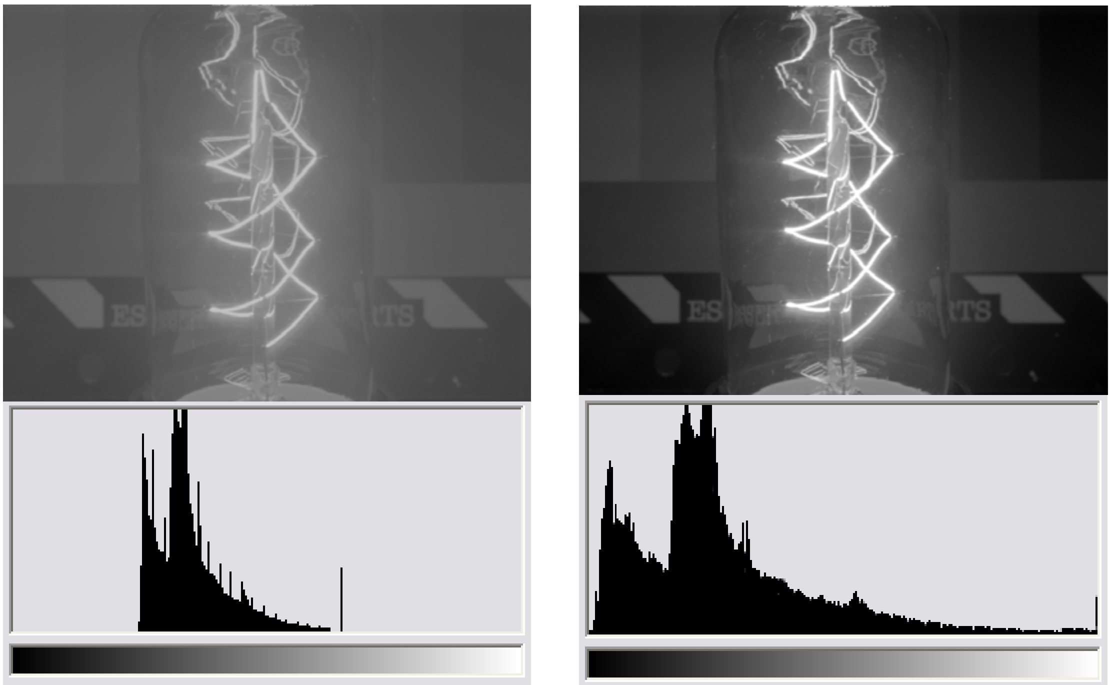

Fig. 6: HDR image capture and histogram with minimal contrast (le.) and with optimum contrast after a contrast adjustment (ri.)

For improved display on the screen or when printed, the histogram can be spread to optimally utilize the possible brightness levels. For this purpose, the dark parts of the image are further darkened via an LUT characteristic[2] and the light parts of the image are brightened. Thus the human eye can better differentiate between the different brightness levels; the image has more contrast.

It must be noted, however, that subsequent processing with a computer will not yield more data. Therefore, subsequent contrast adjustment via software is not necessary for use in image processing. The computer can differentiate between the differences in brightness without contrast adjustment.

Advantage of greater bit depth with contrast adjustment

The bit depth in the output image is crucial for contrast adjustment. The following figures illustrate this. In the example from *Fig. 7,* the 8-bit output image contains fewer than 100 brightness levels, as there are no dark or very bright parts. The image is low-contrast.

With a contrast adjustment, the values of the histogram are spread in such a way as to create a contrast-rich image. The fewer than 100 brightness values are now distributed across levels

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[1] Diagram showing the distribution of brightness values of an image. The brightness values (0-255 with 8 bits) are applied to the x-axis, and frequency to the y-axis.

[2] *Look Up Table*: Tabular assignment of input and output values, which makes calculation easy.

0 to 255; gaps arise in the histogram and are visible as jumps in brightness in the resulting image (see *Fig. 7*, bottom histogram).

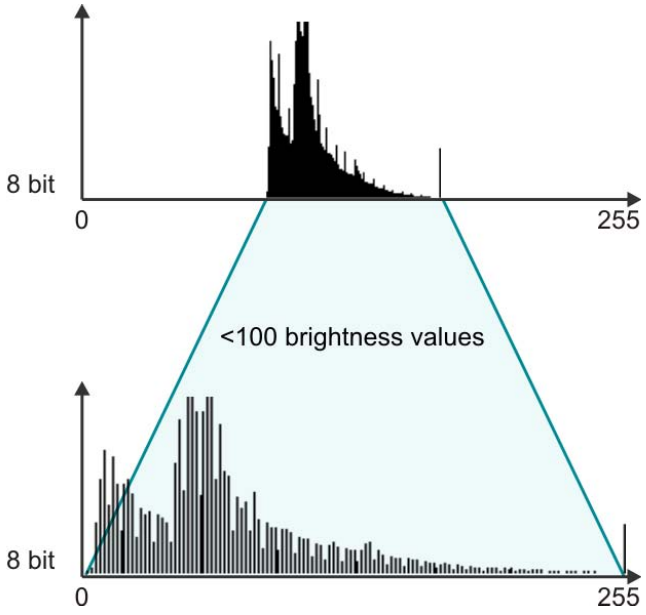

Fig. 7: Contrast adjustment with 8-bit output data

The second example in *Fig. 8* shows the same output image with a 12-bit bit depth right at the time of capture. This image also has low contrast, as it features only average brightness values. The greater bit depth allows the brightness values of the image to be imaged over 1,000 different digital levels, however. The entire histogram includes 4,096 values in the 12-bit image (in contrast to 256 values with 8 bits).

This means that a contrast adjustment can now be made for screen display without a reduction in quality. The 1,000 values of the output image are distributed over the 256 values of the 8-bit target image in such a way that optimum contrast is the result. The large number of output values means that there are no gaps in the histogram (see *Fig. 8*).

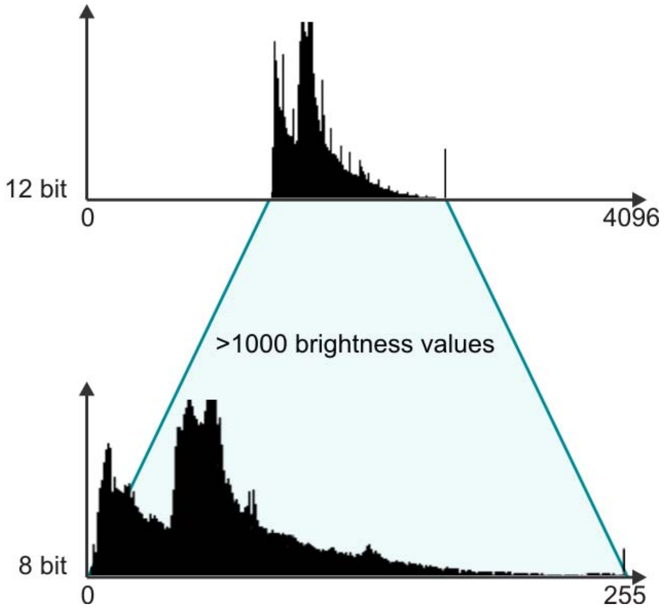

Fig. 8: Contrast adjustment with 12-bit output data

This type of contrast adjustment can already be done in the camera when an image is digitized in 12 bits and transferred in 8. In this case, optimum utilization of the 8-bit data is also important for image processing.

Contrast adjustment with HDR sensors

Contrast adjustment plays an important role, especially with HDR sensors. Since the dynamic range of the sensor is often greater than that of the scene, dull images result. Contrast adjustment as in *Fig. 6* (Page 8) improves the visual impression of these images.

3 Creating HDR images

There are several ways to create HDR images. Four common methods are presented in the following. The main difference between the methods is whether a conventional sensor with a linear characteristic, a conventional sensor with a non-linear characteristic or a real HDR sensor with a logarithmic characteristic is used. Multiple exposure plays a special role and is also mentioned for completeness.

3.1 HDR image capture with linear sensors

3.1.1 Method of functioning of linear sensors

The pixels of a conventional CCD or CMOS sensor generate an electrical charge proportional to the amount of light that strikes them. The charge carriers are accumulated for the duration of the exposure time, and the charge present for each pixel is read out at the end of the exposure time. The dynamic range of such a sensor is limited in the upward direction by the saturation of the pixels. The graphic in *Fig. 9* shows via the characteristic that a conventional linear sensor can only image a very limited dynamic range of the scene. The remaining areas cannot be imaged due to the saturation.

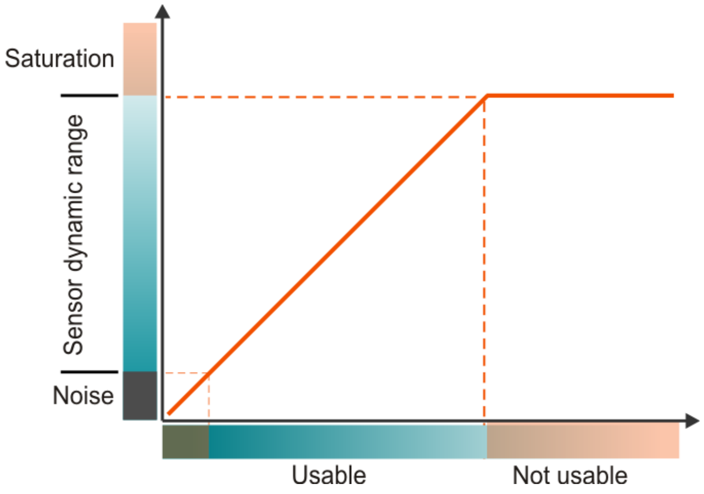

Fig. 9: Image capture with linear sensor

When saturation is reached with the sensor, additional light leads to overexposure. With CCD sensors, the so-called blooming effect also occurs. This involves charge carriers from overexposed pixels "flowing" into the neighboring pixels, which causes whole areas of an image to appear white (the image data is lost in this case).

To prevent overexposure, the aperture can be closed or the exposure time reduced. Both cause the dark areas to contain noise; the image data is also lost in this case.

Fig. 10: CCD sensor with correct exposure (le.) and overexposure (ri.) with blooming

3.1.2 Linear sensor with multiple exposure

Multiple exposure is a method frequently used in digital photography, in particular, to image scenes with high dynamic range. With multiple exposure, an image is captured with the correct exposure and then again at least twice with underexposure and overexposure. In the underexposed image captures, very bright areas are imaged well without some areas outshining others. In overexposed captures, the otherwise too dark areas of the image are displayed well, while bright areas are outshined. These image captures are consolidated into one image with high dynamic range using a so-called tone mapping operator. This technology enables, in principle, an unlimited dynamic range to be achieved. This method is only suitable for industrial use to a degree, as the scene may not change over multiple captures. A long computing time is also required.

Fig. 11: Multiple exposure (top) and HDR image after tone mapping (bottom)[3]

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[3] Images: Kevin McCoy / *Wikimedia Commons*, license: Creative Commons Attribution ShareAlike 3.0

3.1.3 Linear sensor with knee-point characteristic

Some CMOS sensors[4] provide the option of using a piecewise linear characteristic with knee points. With such a piecewise linear characteristic, the form of a gamma or logarithmic characteristic is roughly approximated.

Once a selected duration t_1 (must be shorter than the exposure time) has elapsed, all pixels whose charge exceeds a selected value q_1 are reset to the value q_1. The exposure is continued normally. The graphic in *Fig. 12* (Page 13) shows such a characteristic with a knee point. In this case, the values are selected in such a way that all pixels whose current charge is more than 60% of the maximum value (saturation) are determined after 85% of the exposure time. These pixels are then reset to exactly this value of 60% of the maximum and exposed further. This means that pixels in bright areas of an image are saturated later, and the image has a higher dynamic range.

In the case of sensors with multiple knee points, multiple times t_n and threshold values q_n are defined. With this method, dynamic ranges of a calculated approximate value of 80 dB are achieved. What is disadvantageous here is that the knee points must be readjusted to each exposure situation and that overexposure of the sensor is still possible. In addition, this method is mainly suitable for monochrome sensors, as calculating the correct white balance using different knee points is very difficult with color sensors.

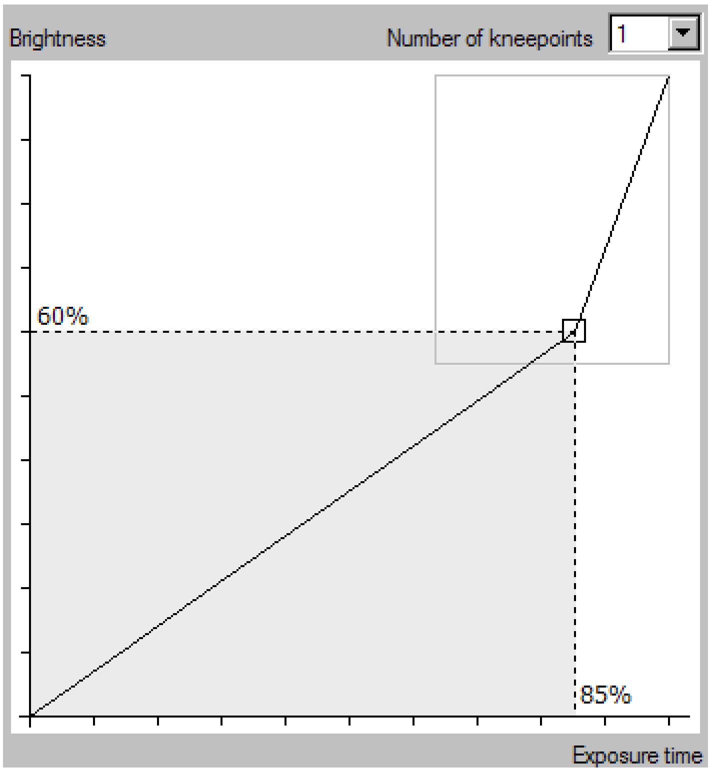

Fig. 12: IDS uEye *camera with HDR knee-point function*

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[4] E.g. Aptina MT9V033, which is used in IDS uEye cameras of type UI-122x/UI-522x, among others

3.1.4 Logarithmic HDR sensors with conventional photodiode

Using the formula in Section 2.1.1, you can calculate that a *linear* 8-bit image with 256 brightness levels can no longer be imaged with a roughly 48 dB dynamic range.

$$D_{8\ Bit} = 20 \cdot \lg\left(\frac{256}{1}\right) = 48.16\ dB$$

To be able to display a dynamic range of 120 dB with a *linear* characteristic, approximately 1 million brightness steps or a bit depth of 20 bits after the sensor would be required accordingly. If however the sensor possesses a *logarithmic* characteristic the scene dynamic range of 120 dB can be digitized with a smaller number of binary steps. The logarithmic pixels perform dynamic compression. This is why a logarithmic characteristic is aimed for with HDR sensors.

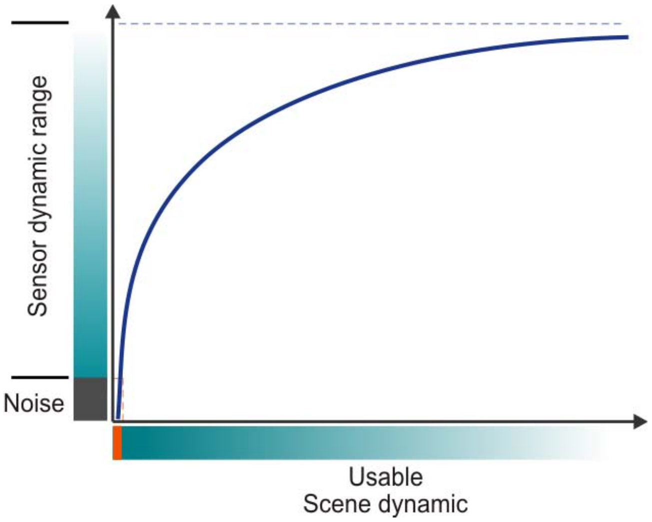

Fig. 13: Image capture with a logarithmic sensor

One possibility for achieving this is the use of a photodiode and a non-linear resistor. Just as with a conventional CMOS sensor, the photodiode supplies a photocurrent that is linearly proportional to the amount of light that strikes it. This is often achieved using one or more MOS transistors wired in series with the diode. The logarithmic characteristic of these transistors yields a logarithmic output voltage (see *Fig. 14*).

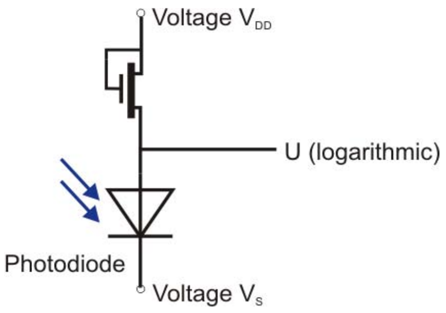

Fig. 14: Schematic structure of an HDR pixel with a logarithmic transistor

Fixed pattern noise (FPN) with HDR sensors

A major disadvantage of this structure is the large portion of fixed pattern noise (FPN). A different offset arises in every pixel due to dark and leakage currents. With conventional linear sensors, this hardly ever occurs. Since the logarithmic characteristic accentuates the differences in brightness in dark areas of an image, these noise patterns often have a very strong effect with HDR sensors.

To avoid FPN and other disadvantages of this pixel structure, there are sensors that work with a linear characteristic in the lower brightness range. The pixels do not switch to logarithmic mode until a certain threshold is reached. LinLog™ sensor technology uses such a combination, which is supposed to combine the advantages of linear and logarithmic characteristics. A disadvantage of this combination, however, is that the transition points must be adjusted again between the two modes for every new exposure situation.

3.1.5 Logarithmic HDR sensor with solar cell

The FX4 HDR sensor used in IDS *uEye* cameras works based on a completely different principle. No conventional photodiodes are used in this sensor, rather miniaturized solar cells are used. These are in principle also photodiodes, but are operated differently. While photodiodes generate a linear current proportional to the amount of light, solar cells output a logarithmic voltage based on the amount of light. This means that taking a logarithm of the signal afterward is not necessary. The characteristic is already truly logarithmic.

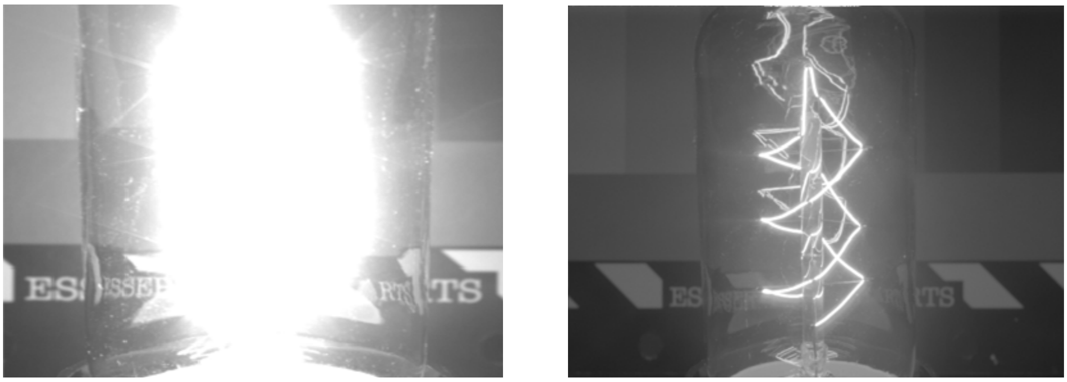

Fig. 15: 40 W light bulb captured with CCD sensor (le.) and FX4 HDR sensor (ri).

4 FX4 HDR sensor: Method of functioning

Thanks to a new pixel structure type, it was possible to develop a sensor with a truly logarithmic characteristic exhibiting no *fixed pattern noise* (see above). The method of functioning of this sensor is explained in the following.

4.1.1 Pixel structure

The FX4 sensor used in *uEye* HDR cameras features a patented pixel structure that provides a truly logarithmic display with effective suppression of fixed noise (*fixed pattern noise*, see above).

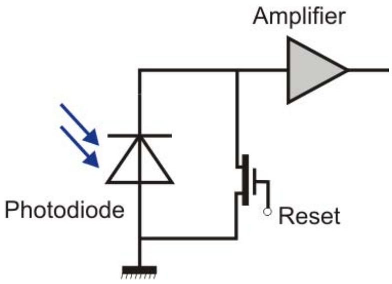

Fig. 16: Schematic structure of the FX4 pixel

The photodiode is operated as a solar cell here and generates a voltage that is precisely logarithmic in accordance with the amount of light that strikes it. The signal is amplified in the pixel and output analog. In *uEye* cameras, an external A/D converter handles digitization with 14-bit resolution. The voltage range of the A/D converter is greater than the maximum output voltage of the sensor to prevent overcontrol of the digital level and to compensate for temperature drift of the sensor.

The FX4 sensor achieves a dynamic range of 120 dB. Note that the HDR technology is not to be equated with increased sensitivity of the sensor. The light sensitivity of the FX4 HDR sensor is within the range of current CCD and CMOS sensors.

4.1.2 Exposure

The FX4 sensor does not feature an integrative principle, i.e. there is no exposure time. The HDR pixels output a voltage corresponding to their current light amount at all times. This voltage level is polled at the desired frame frequency. For 30 frames per second, for example, the light value currently measured by each pixel is output 30 times a second. The analog voltage values are digitized by a downstream analog/digital converter.

4.1.3 Readout mode

Pixel values are read out line by line (*rolling readout) with the FX4.* Due to the slight time offset between reading out a line *n* and the next line *n+1*, the so-called *rolling-shutter effect* may be seen. Here, objects that move through the field of view at a high speed may be displayed geometrically distorted. If a square object moves horizontally in relation to the image, for example, it will appear as a parallelogram in the image, as the upper parts of the object are imaged earlier than the lower parts.

The readout duration for an entire image is t_{image} = 1/frame rate; the offset between two lines is thus t_{line} = t_{image}/frame height.

The sensor works in *progressive scanning* mode, where complete images are read out (in contrast to *interlaced scanning*, where fields are read out using the interlacing method).

4.1.4 Correction of fixed pattern noise (FPN)

The FX4 features an effective mechanism for almost completely eliminating pattern noise. Before reading out from the sensor, the photodiode is short-circuited by a reset transistor (see *Fig. 16,* Page 16). The signal output by the pixel only contains the current offset and can be subtracted from the image captured directly thereafter. This process is carried out line by line before every image capture.

5 Application notes

5.1 Typical areas of use

Cameras with HDR sensors are mainly suitable for the following two areas of use:

1. Environments with a very high dynamic range
2. Environments with strong and unpredictable brightness fluctuations.

Environments with a very high dynamic range include the following, for example:

- Automotive/traffic: Here, situations often occur where a sensor is exposed to a very bright light, e.g. from the headlights of an advancing vehicle, but where data in dark areas of the image (e.g. vehicle interior) must be evaluated at the same time.
- Welding: The welding arc generates a very bright light, which makes it impossible to identify the object being welded or the weld seam using conventional sensors.
- Paints and glossy surfaces: Reflections and glossy spots on mirroring surfaces require sensors with increased dynamic range.
- Kiosk applications: Portrait images of persons operating ATMs and other free-standing self-service applications are required. In unfavorable lighting conditions, the dynamic range of conventional sensors is no longer sufficient.

Environments with very strong fluctuations in brightness are often seen with these applications:

- Security technology and monitoring: A high scene dynamic might arise in a sunny scene with quickly-moving intermittent cloud cover. Controls such as the auto iris in monitoring cameras are often overburdened in such situations.

5.2 Instructions for use

When using cameras with HDR sensors in general, and the FX4 sensor in particular, the following information should be heeded.

5.2.1 Display and processing of HDR images

As explained in Sections 2.3.2 and 2.3.3 (Pages 7 and 8), greater bit depths are advantageous for processing, especially of HDR images. To fully utilize the dynamic range of the images, they should be transferred with a bit depth of 12. This allows the relevant areas of the image to be processed further with the best quality possible using software.

For unaltered display of the images, uEye HDR cameras feature an approximately linear mode in which the image contrast corresponds to that of conventional sensors. The output values of the sensor are squared in the camera for this purpose. The result of multiplying $log(x) * log(x)$ corresponds to a characteristic with gamma equal to 0.5 with good approximation and is therefore well suited for display on a screen (see also Section 2.2.2, Page 5). Note, however, that the usable dynamic range is reduced due to the squaring. We do not recommend using this mode for further processing of image data.

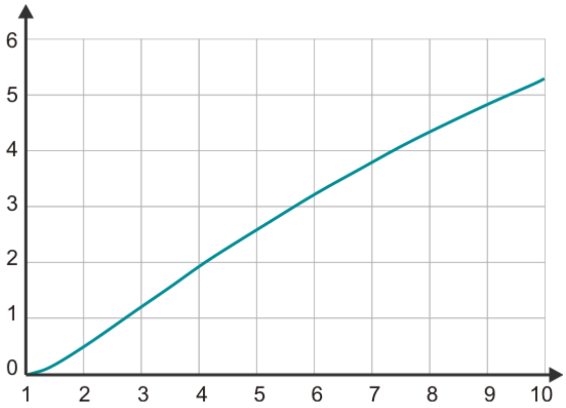

Fig. 17: The function $\log(x) * \log(x)$ approximately corresponds to a characteristic where $\gamma = 0.5$

5.2.2 Selecting lenses

Due to the extremely high dynamic range of the HDR sensor, any lens reflections always emerge more pronounced in lenses than when conventional sensors are used. With untempered lenses, the reflection can be more than 4% of the amount of light captured. Light reflected in this way is mirrored on successive lens elements and ultimately appears as a distracting light spot in the image. To achieve good results with cameras featuring HDR sensors, the individual elements of the lens must be given a high-quality anti-reflective coating.

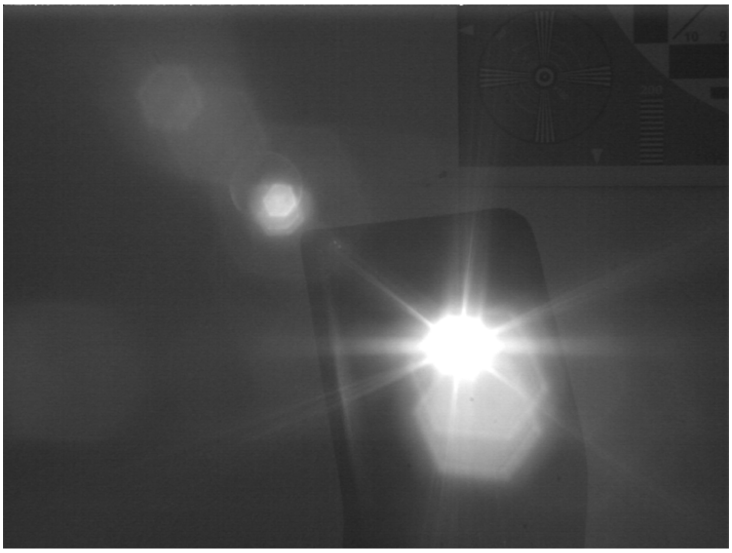

Fig. 18: Strong lens reflections in a C-Mount lens.
The hexagonal shape of the aperture is clearly identifiable.

5.2.3 Flash mode and pulsed lighting

Since HDR sensors such as the FX4 do not integrate charges like conventional sensors, there are limitations in flash mode. When reading out the sensor, the amount of light striking each pixel at that exact moment in time is measured. For this reason, a flash must remain active during the entire readout duration to light up the entire image. In the case of a sensor with *rolling readout*, the light source would have to be illuminated during the entire readout duration (t = 1/frame rate) to light up the image evenly, which is generally not possible with high-power flashes.

Another effect of the lack of integration on the sensor results from quickly pulsating light, such as that originating from LED and laser light sources and electric arc welding. The fluctuations in the brightness of the light source caused by the pulsation are visible as transitions from light to dark in the image, where their spacing depends on the light source frequency.

5.2.4 Movement

When capturing quickly-moving objects with the FX4 sensor, observe the information listed in 4.1.3 Readout mode (Page 16).

6 Appendix

6.1 FX4 HDR sensor specifications

Sensor type	HDR CMOS sensor
Pixel size	10 µm x 10 µm
Resolution	768 x 576 pixel (CCIR)
Dynamic range	120 dB
Max. frame rate	50 fps
Readout method	Rolling readout
Digitization	14-bit A/D converter, output: 8- or 12-bit

6.2 Contact and other information

With the uEye® line of cameras, IDS Imaging Development System GmbH offers a series of modern USB and GigE cameras for image processing in industrial and non-industrial environments. CMOS and CCD sensors from well-known manufacturers provide resolutions from VGA to 10 megapixels and frame rates up to 100 full frames per second. Using the comprehensive, freely available uEye® software package allows any camera to be integrated into image-processing libraries or used for own applications.

More information on IDS and uEye® cameras can be found at www.ids-imaging.com.

If you have any questions about HDR technology or would like a non-binding offer, feel free to contact us:

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E-mail: sales@ids-imaging.com