HOCHSCHULE OSNABRÜCK

UNIVERSITY OF APPLIED SCIENCES

Optoelectronic

Pixel size sensitivity

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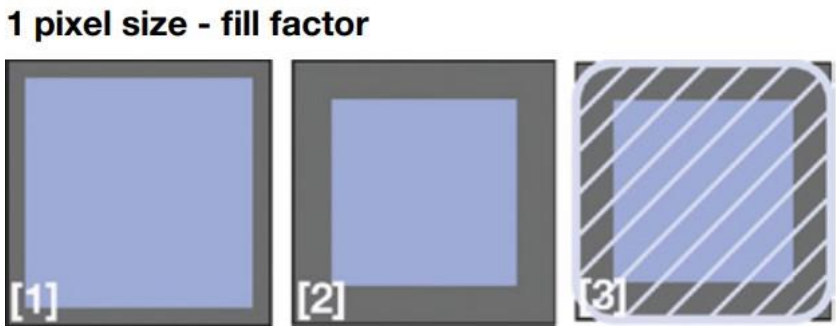
Table of content

Introduction:

To dispel the notion that "bigger pixel image sensors are always more sensitive than small pixel sensors," the link between an image sensor's pixel size and its sensitivity is thoroughly explored.



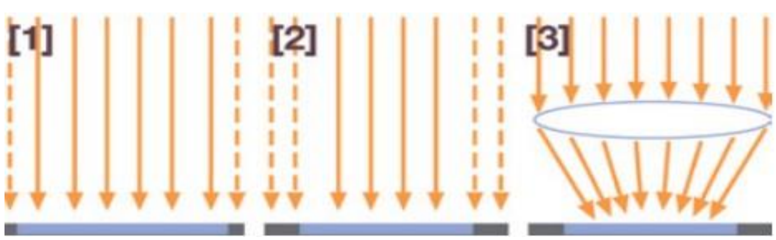
Different fill factors for pixels (the blue area corresponds to the light-sensitive area) :

75% fill-factor pixels

50% fill-factor pixels

A pixel with a 50% fill factor plus a top-mounted microlens

Since a portion of an image sensor pixel is always used for transistors, electrodes, or registers, the fill factor of a pixel indicates the ratio of the light sensitive area to the entire area of a pixel. They are a part of the pixel's structure on the relevant image sensor (CCD, CMOS, sCMOS). The light signal that the pixel detects might only come from the light-sensitive component.



Pixel Sizes:

Pixel size and sensitivity are two important factors that determine the quality of digital images. Pixel size refers to the physical dimensions of an individual pixel on an image sensor, while sensitivity refers to the ability of the sensor to capture light. These two factors are interrelated and can impact the overall image quality.

The size of a pixel affects how much light it can capture, which in turn affects image quality. Larger pixels can capture more light, making them more sensitive to light. This results in improved image quality, particularly in low-light conditions. However, larger pixels can also lead to lower resolution, as there will be fewer pixels on the sensor.

Cross-sectional view of pixels with various fill factors and the light beams that impinge on them (the blue area refers to the light-sensitive area) (orange arrows). Rays of light that have been dashed together show that they do not contribute to the signal.

75% fill-factor pixels

50% fill-factor pixels

50% fill-factor pixels with a top-mounted microlens in case the fill-factor is too low

Micro lenses are frequently used to increase fill factor. These lenses focus light into the light-sensitive region of the pixel after collecting light that is impinging on it.

fill factor	light sensitive area	quantum efficiency	signal
large	large	high	large
small	small	small	small
small + micro lens	larger effective area	high	large

Although the use of micro lenses is always advantageous for pixels with fill factors below 100%, there are still some technological and physical restrictions to take into account.

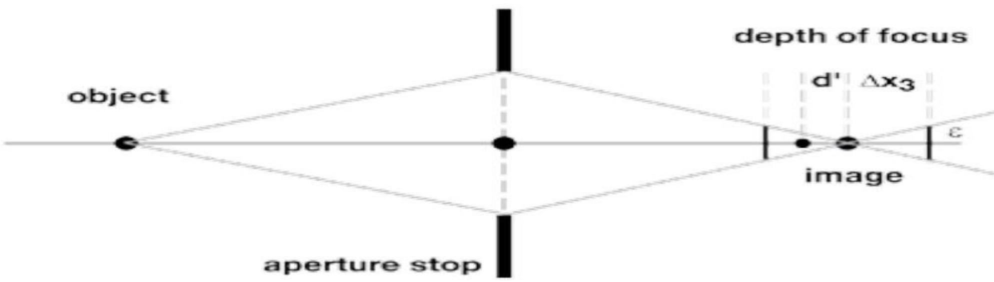
Two instances of moderate fill factors are the global shutter 5 or 6T pixel of a CMOS sensor, which has a 50% fill factor generated by the transistors and electrical leads, and the pixel of an interline transfer CCD image sensor, where 50% of the pixel space is used for the shift register.

Even so, some large pixels might benefit from the use of a less efficient microlens, for instance, if the lens's purpose is to stop too much light from entering the pixel's periphery.

Pixel Size - Depth of Focus:

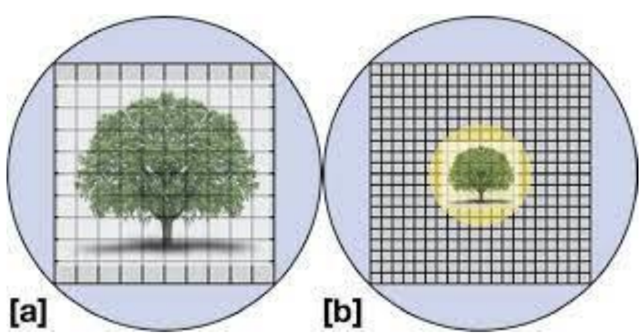
An illustration of the concept of depth of focus, which is the range of image distances over which blurring does not exceed a predetermined threshold.

The relationship between the distances of an object and an image is determined by the image equation. The image is not rendered useless if the object is closer to the lens system or the image plane is slightly shifted. According to the image equation, the greater the deviation from the distances, the blurrier it becomes.



Sensitivity:

Sensitivity, also known as ISO, refers to the ability of an image sensor to capture light. A higher ISO value results in increased sensitivity to light, allowing for better images in low-light conditions. However, increasing ISO also increases image noise, which can degrade image quality.



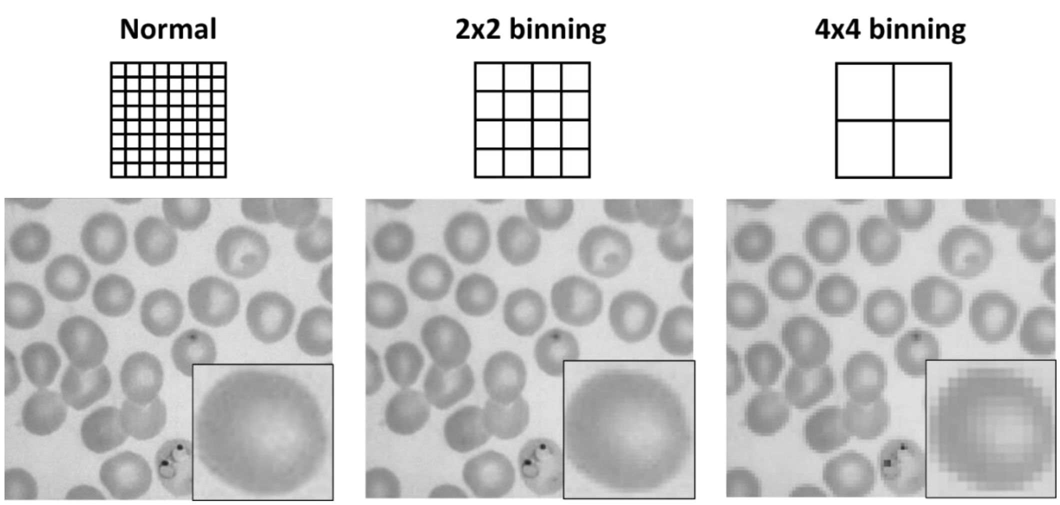
Impact of Pixel Size and Sensitivity:

Pixel size and sensitivity are two important factors that can greatly impact the quality of images captured by digital cameras or other imaging devices.

Pixel size refers to the physical size of the individual pixels on the sensor or image chip of a camera. Generally, larger pixel sizes can capture more light and provide better dynamic range, resulting in higher image quality. This is because larger pixels are more sensitive to light and can capture more photons, which reduces the noise in the image and provides better color accuracy. Larger pixel sizes also enable higher resolution imaging, allowing for more detail to be captured in the image.

On the other hand, sensitivity refers to the ability of the camera to capture images in low light conditions. Cameras with high sensitivity can capture images in low light without introducing too much noise or distortion, resulting in better image quality. This is particularly important in situations where natural or artificial lighting is not adequate, such as night photography, astrophotography, or indoor photography.

Both pixel size and sensitivity are important factors to consider when choosing a camera or other imaging device, as they can greatly impact the quality of the images you can capture. However, it is worth noting that other factors, such as lens quality, image processing algorithms, and camera settings, can also have a significant impact on image quality.



Most of the time, the concepts of depth of field and depth of focus only apply to perfect optical systems. The depth of field can only be utilized for blurring that is significantly more severe than that caused by the system's aberrations if the optical system has any aberrations.

If the effect of pixel size on a camera's sensitivity, dynamic range, and image quality were investigated, numerous characteristics could be altered or maintained. Comparison of the overall area and resolution for pixels In an effort to find a solution, various approaches are taken in the sections that follow.

In order to facilitate comparison, square-shaped image sensors that fit within a lens's image circle or imaging area are assumed.

The radiant flux per unit area, also known as irradiance E [W/m2], is assumed to be constant over the image circle's surface for comparison. Let's say that the left image sensor in figure 6 has smaller pixels but a higher resolution, such as 2000 x 2000 pixels at a pixel pitch of 10 micrometers; on the other hand, the right image sensor in figure 6 has 6, sensor [2]) has 1000 x 1000 pixels with a pixel pitch of 20 micrometers.

It is possible to examine a single pixel, but this ignores the different resolution, or to compare the same resolution using the same lens, but this equates to comparing four pixels to a single pixel. In most cases, it is also assumed that the pixels of both image sensors have the same fill factor for the purposes of the considerations. The small pixel measures the signal m and has its own readout noise r0. As a result, a signal-to-noise ratio s can be calculated for two crucial imaging scenarios: low light, where photon noise is more prevalent, and bright light, where readout noise is more prevalent.

Consideration on signal and SNR for different pixel sizes same total area.

pixel type	signal	readout noise	SNR low light	SNR bright light
small pixel	m	r_0	s_0	s_1
large pixel	4 x m	$> r_0$	$> s_0$	2 x s_1
4 small pixels	4 x m	2 x r_0 [iv]	2 x s_0	2 x s_1

The relationship between SNR and pixel area remains valid, meaning that the larger the pixel and, consequently, the greater the SNR.

However, in the end, this indicates that a single pixel with a total area that fits within the image circle provides the highest SNR:

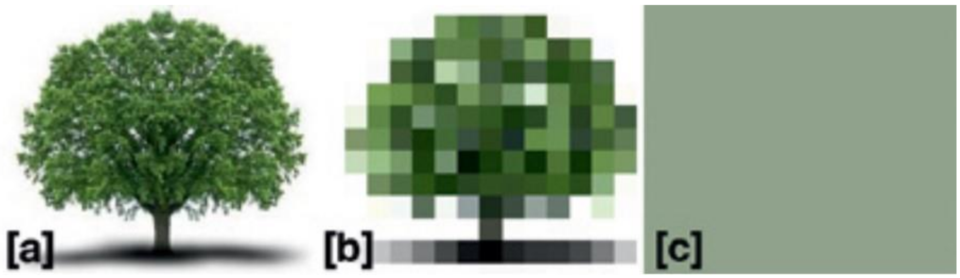


Illustration of three resulting images which where recorded at different resolutions:

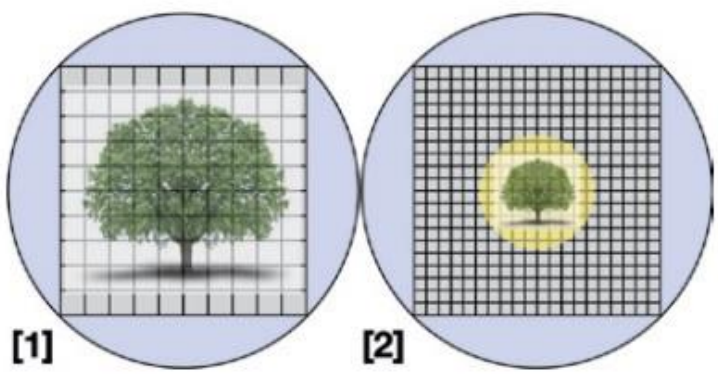
1. High resolution
2. Low resolution
3. Pixel resolution.
4. Constant Resolution

Constant Resolution:

Constant: Aperture & object distance

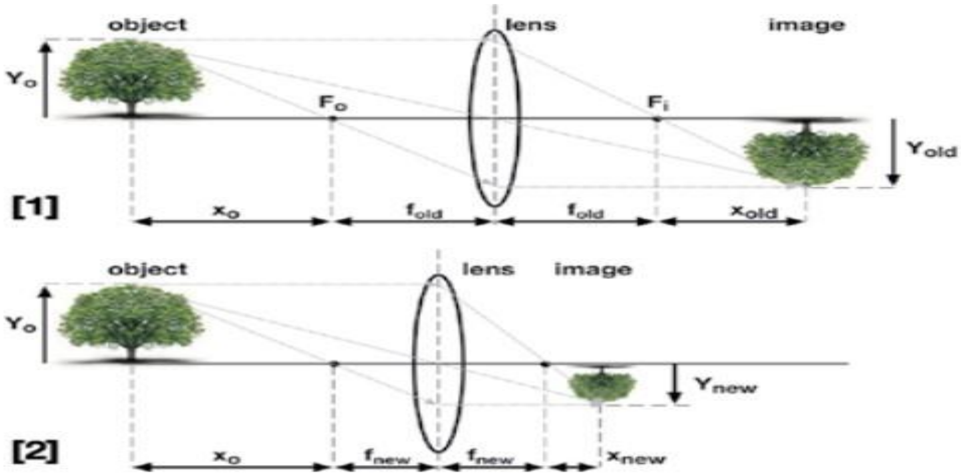
Variable: Pixel size, focal length, area & irradiance

Two square-shaped image sensors make up the picture circle of the same kind of lens. Lenses with varying focal lengths are required because the tree is photographed with the same number of pixels: The pixels of an image sensor are four times larger than those of a sensor[1].



If the pixel count should remain constant at the same object distance, consider this additional comparative option. Changing the lens's focal length in front of the tiny pixel image sensor would be necessary to accomplish that. because it was necessary to focus the energy (information) that had previously been spread out over a larger visual area.

- Example of two imaging circumstances that need to be contrasted: This special lens captures everything on the large pixel sensor [1]. [2] This lens has a shortened focal length that allows it to record images on a sensor with smaller pixels.



Limitations:

While pixel size and sensitivity are important factors that can greatly impact the quality of images, they do have certain limitations.

One limitation of pixel size is that as the size of individual pixels increases, the resolution of the image decreases. This is because larger pixels require more physical space on the image sensor, which can reduce the number of pixels that can be packed into a given area. Therefore, there is a trade-off between pixel size and resolution, and finding the right balance is crucial to achieving high-quality images.

Another limitation of sensitivity is that increasing the camera's sensitivity can also increase the amount of noise or grain in the image. This can be particularly noticeable in low-light photography, where the camera may need to amplify the signal from the image sensor to capture enough light. High sensitivity can also reduce the dynamic range of the image, leading to loss of detail in highlights and shadows.

It is also worth noting that pixel size and sensitivity are just two factors that impact image quality. Other factors, such as lens quality, image processing algorithms, and camera settings, can also have a significant impact on image quality. Therefore, achieving the best possible image quality requires a careful balance of many different factors.

limitations	
size limitation for micro lenses	For pixels larger than 12µm pixel pitch the stack height of the process to make a good micro lens can't be made high enough to generate a good lens. This stack height is proportional to the area, which should be covered[ii]
CMOS pixels have limited fill factor	due to semi-conductor processing there has always to be 25% of the pixel area covered with metal => maximum fill factor = 75%
light sensitive areas larger than 25µm x 25µm	are difficult to realize because diffusion length and therefore the probability for recombination increase

Fill Factor:

The proportion of a pixel's light-sensitive area to its total area is referred to as its fill factor. This is due to the fact that a transistor, electrode, or resistor always occupies a portion of an image sensor pixel. The readout technology or pixel architecture of the corresponding image sensor (CCD, CMOS, or sCMOS). The pixel can only detect a light signal from the light-sensitive portion. Usually, adding micro lenses increases the fill factor if it is too low. A lens is used in microlensing to focus light on the pixel's light-sensitive area by collecting light that hits the pixel.

Total Area / Resolution:

When examining the effect of pixel size on camera sensitivity, dynamics, and image quality, there are various parameters that can be changed or kept constant.

There are numerous advantages to larger pixels, including a larger full well capacity. One important parameter that influences the image sensor's overall dynamic and, consequently, the camera system is the pixel's full well capacity.

Although pixel architecture, layer structure, and well depth all have an impact on this full well capacity, there is a general correlation with the light-sensitive area as well.

This is also true for the pixel's electrical capacity and the thermally generated dark current. Dark current and capacity both contribute to the noise behavior, so larger pixels also display more readout noise.

The signal-to-noise ratio may suffer as a result of this in low-light situations.

Sensor and Pixel Sizes:

A sensor and a pixel are two different things, but they are closely related in the context of digital photography.

A sensor is an electronic device that is used to convert light into an electrical signal. In a digital camera, the sensor is responsible for capturing the light that passes through the lens and converting it into a digital image that can be stored on a memory card. The most common type of sensor used in digital cameras is the CMOS (Complementary Metal-Oxide-Semiconductor) sensor, although some cameras still use CCD (Charge-Coupled Device) sensors.

A pixel, on the other hand, is a tiny picture element that makes up a digital image. Each pixel represents a single point in the image, and the color and brightness of the pixel determine what that point looks like in the overall image. A digital image is made up of millions of pixels arranged in a grid, and the more pixels in the image, the higher the resolution and detail of the image.

In a digital camera, the sensor is made up of millions of individual pixels, and each pixel is responsible for capturing the light that hits it and converting it into an electrical signal. The size and quality of the pixels on the sensor can affect the overall image quality, and cameras with larger and more advanced sensors tend to produce higher-quality images.

Sensor and Pixel Sizes of CDD and CMOS Sensors:

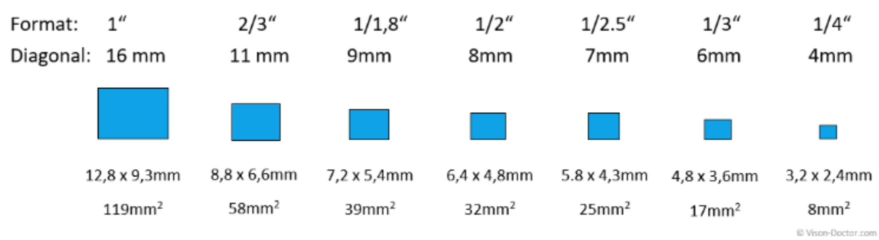
CCD and CMOS sensor’s progressive technological advancements make it possible to fabricate ever-smaller semiconductor structures. In general, the sizes of sensors and pixels are getting smaller so that more sensors can be cut from a wafer. This is made possible by the electronics' improved noise behavior and the pixels' increased sensitivity.

Comparing cameras with different sensor and pixel sizes with the same resolution is worthwhile as technical limits are reached in this regard as well. This is especially true if:

1-There is little light. 2-Images with low noise and a high dynamic image response are needed. 3-Precise measurements are expected. A larger sensor with more pixels is almost always the better option technically, but the price is always higher.

Sensor Sizes of Standard Cameras:

Depending on the camera and the resolution used, conventional image processing cameras have sensors of various sizes. C-mount or CS-mount optics are used by the majority of small-sensor cameras. The C-mount screw has a thread pitch of 1/32 inch and a diameter of 1 inch (25.4 mm).
Standard cameras employ very small sensors with image diagonals ranging from 4 to 16 mm. These sensors' dimensions are also listed in inches. The diagonal of a one-inch sensor is 16 mm.



The fact that pick-up tubes were utilized in television cameras up until the middle of the 1980s and were significantly superior to CCD or CMOS sensors, which were developed in the late 1960s, is the only historical explanation for the inch data of CCD and CMOS sensors.

The actual image converter of the tube cameras was contained within a glass vacuum tube; the various pick-up tubes were classified according to the size of the glass bulb on the outside, among other things.

The light-sensitive surface inside the tube was naturally smaller, and the diagonal made up about two thirds of the outer diameter. CCD sensors that are equivalent to cathode ray tubes and must be used to precisely cover this surface. Even though this is not the actual size of the CCD sensor, a CCD with a light-sensitive surface that is the same as a half-inch tube was referred to as a "1/2-inch sensor."

Large-format sensor sizes of area scan cameras or line scan cameras:

High-resolution area scan or line scan cameras use sensors that are several centimeters in size or larger. These sensors' dimensions, which are typically not defined, are determined by their resolution and pixel sizes. Everything is permissible; The only constraint is money.

A line scan camera with 2048 pixels has a line length of 10.48 mm at 10 m pixels; The sensor is already 28.6 mm long with 14 m pixels. Sensors with diagonals greater than 20 mm no longer require the use of the C-mount lens connector.

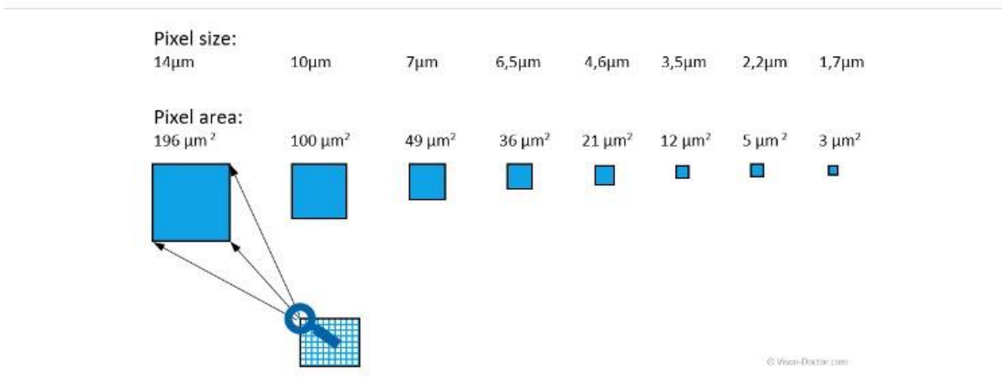
These cameras typically use M42 to M72 or Nikon bayonet (F-mount) connectors for lenses. High-resolution sensors with big pixels can only be used to build line scan cameras with up to 12k pixels or area scan cameras with up to 28 million pixels.

Pixel Sizes of CDD or CMOS Sensors:

As sensors become smaller and smaller, pixel sizes decrease. At the moment, consumer cameras with 8 to 12 megapixels and a price tag of 200 euros have sensors with pixels that typically measure 1.7 meters in size. Consequently, there is only about 3 m2 of light-active surface per pixel. This results in a very loud sensor noise when the lighting is poor. When cameras are used for quality control, this is completely unacceptable.

Machine vision cameras (C-mount) with resolutions ranging from VGA to 2 megapixels typically produce signal outputs that are noticeably superior due to their larger light-active surfaces and pixels of 4.6 to 6.5 m. If you want noise-free images and precise measurement results, look for cameras with larger sensor pixels, even if they cost more.

Typical pixel sizes of industrial cameras



Pixels with an edge length of 14 or 10 m are preferred in line scan cameras. Due to the high line frequency of 18 Hz, for instance, the maximum exposure time for one taken image line is 1000 times 2000, or 55 seconds. The light-active surface of the pixel will never be large enough in this scenario.

Full Well Capacity of a Pixel:

The number of electrons that a pixel element can hold before becoming completely saturated is described in this specification. A structure-sized pixel of 5.5 m can store approximately 20,000 electrons, while a 7.4 m pixel can store 40,000 electrons.

The higher the maximum signal-to-noise ratio, the larger the full well capacity. Pixel saturation only requires about 1,000 photons for consumer cameras with 1.7 m pixel sizes. Other noise effects (photon noise, digitalization noise, and dark noise) can already take on significant scales when digitalization is done with 8, 10, or even 12 bits. These effects interfere with the signal and have a devastating effect on the image.

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Important for Machine Vision:

Pixel size increases the amount of light required to capture an image. In situations where inspection times are short, the lack of light can easily be a problem.

When there isn't much light, small pixels clearly produce coarser images than large pixels, and their dynamic image responsiveness is reduced. Noise is disruptive to the application. Make use of LED flash controllers or intense illumination to produce more light.

Sometimes having a lot of megapixels doesn't help. For architectures with fewer pixels, high-quality optic imaging and high-resolution lenses are required. Otherwise, images are produced that are pixel-dense and blurry without any actual structural information.

Additionally, a very precise technical alignment of the sensor is required because using small camera pixels significantly reduces the depth of field. The housing tilting of a 5 m sensor only needs to be half as big (+/1 15 m at aperture = 2.8) as it would be for 10 m structurally large pixels. To avoid having the best sensor in the camera fail, look for suppliers of high quality.

Resolution and Light Sensitivity:

When the size of a CMOS imaging sensor array is fixed, the only way to increase sampling density and spatial resolution is to reduce pixel size. Light sensitivity, on the other hand, decreases as pixel size decreases.

Light sensitivity and spatial resolution must therefore be sacrificed in light of these limitations. Since this tradeoff involves the interaction of numerous system components, we characterized performance using a comprehensive system simulation.

System simulations that predict output are used to quantify the spatial resolution and light sensitivity of various imaging sensors with varying pixel sizes but the same dye size in this study.

1- Simulated Events:

Scene, Optics, Sensor, and Processor are the four main software modules that make up the Image Systems Evaluation Toolkit (ISET). Using a variety of specialized tools and functions included in each module, the user can experiment with various designs and component attributes, configure settings, and calculate pertinent metrics. As the input to the simulated digital camera, the Scene module displays the spectral radiance (photons/sec, nm, sr, m2) at each pixel in the sampled scene as a multidimensional array.

The optics module converts the scene radiance data into an irradiance image at the sensor. The method by which the scene radiance image is converted into irradiance is determined by the properties of the simulated optics. The Sensor module converts irradiance into a sensor signal. A comprehensive optical and electrical model is included in this transition.

The processor module turns the electron count into a digital image, which is then displayed on a mockup color display. Algorithms for color balance, demos icing, and color conversion to a calibrated color space are included in this module.

2- Performance of a sensor:

System signal-to-noise ratio (SNR) and system modulation transfer function (MTF) performance summaries are used to describe light sensitivity and spatial resolution, respectively. These measurements are influenced by a variety of sensor characteristics, such as read noise, dark noise, conversion gain, and voltage swing. Each of these characteristics, which change with pixel size, has an impact on the MTF and SNR.

2.1- Sensitivity to Light:

Well capacity decreases as a result of pixel size. The short and long exposure times, as well as the high and low brightness levels of the scene, are affected by this. Because they receive fewer photons through their aperture than large pixels do, small pixels saturate at lower photometric exposure settings. These properties have an impact on sensor dynamic range and signal-to-noise ratios.

2.3- Resolution of Space:

The modulation transfer function (MTF) describes an imaging system's capacity to capture visual contrast across a variety of spatial frequencies. We evaluated the MTF system in accordance with ISO standard ISO 12233. The system's response to a sloped edge is evaluated with this method. The edge-to-edge lines measure the step response in a variety of phase relationships in contrast to the pixel sampling grid. Combining these responses results in the computation of the system MTF. Figure 3 depicts the MTF of the green sensor channel for the simulated color imaging sensors. Sensors with tiny pixels can, as expected, capture and preserve information at higher spatial frequencies. These graphs are summarized by the spatial frequency at which the amplitude drops to 50% of the maximum value.

3. Picture Quality Tradeoffs

Figure 5, which plots the MTF50 against the corresponding of MPE30 for every one of the reenacted variety imaging sensors, shows the compromise between spatial goal and light responsiveness. Higher values for MTF50 and 1/MPE30 indicate better image quality. There is a correlation between high MTF50 values and smaller pixels and low 1/MPE30 values. There is a correlation between high 1/MPE30 values and larger pixels and low MTF50 values. There isn't an obvious optimal point in the presented tradeoff function.

Conclusion:

The quality of digital images is largely determined by pixel size and sensitivity. However, the relationship between size and light sensitivity is not always linear. Each photographer's particular requirements will determine the best combination of sensitivity and pixel size.

The quality of digital images is largely determined by the size of the image sensor and its pixels. While larger sensors can improve resolution, they also make camera bodies and lenses bigger. Typically, larger pixels are more sensitive to light, but they may also result in lower resolution. Each photographer's specific needs and requirements will determine the best combination of sensor and pixel sizes.

The quality of digital images is largely determined by resolution and light sensitivity. Each photographer's specific requirements will determine which combination of ISO and resolution is best. An image with a higher resolution has more detail and clarity, but it also has a larger file size. Image noise can increase with ISO, but it can also improve low-light performance.

It is not always the case that larger pixels are more sensitive to light because of the complex relationship between pixel size and sensitivity. The amount of light a pixel can capture is influenced by its size, but light sensitivity can also be affected by sensor technology and image processing. Each photographer's particular requirements will determine the best combination of sensitivity and pixel size.

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