Saturation (imaging)

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Synonyms

- Clipping

Related Concepts

- Overexposure
- Radiometric response functions
- Full well capacity
- Blooming
- Dynamic range
- High dynamic range imaging

Definition

In imaging, saturation is a type of distortion where the recorded image is limited to some maximum value, interfering with the measurement of bright regions of the scene.

Background

The role of a sensor element is to measure incident irradiance and record that quantity as an image intensity value. However, physical constraints limit the maximum irradiance that can be measured for a given camera setting. In the absence of noise, the mapping from irradiance to image intensity is fully described by the *radiometric response function*, a monotonically increasing function whose range is restricted by the maximum irradiance. Pixels whose intensity corresponds to this maximum are known as saturated.

Saturated pixels contain less information about the scene than other pixels. While non-saturated pixels can be related to the incident irradiance by applying the inverse of the radiometric response function, saturated pixels provide only a lower bound on irradiance. Therefore, estimating the irradiance of saturated pixels is similar to other image “hallucination” tasks such as inpainting [2].

Since many computer vision algorithms assume a linear relationship between sensor irradiance and the measured image intensity, it is important to identify saturated pixels and handle them appropriately. In practice, saturated pixels are often treated as missing values or otherwise ignored.

Theory

In the idealized noise-free case, the image intensity M of a pixel can be described as mapping the incident irradiance I according to the radiometric response function $f(\cdot)$, limited by the maximum irradiance $I_{\max}$,

$$M = f\left(\min(I, I_{\max})\right) \ . \tag{1}$$

For an irradiance of $I_{\max}$ or higher, the image intensity will saturate at its maximum value of $M_{\max} = f(I_{\max})$. Since saturated pixels do not have unique corresponding irradiance values, they provide no direct information about incident irradiance beyond imposing a lower bound of $I_{\max}$.

Identifying saturated pixels is straightforward in practice, since many saturated pixels have the nominal maximum pixel value of $M_{\max}$. Sensor noise and other on-camera processing introduce the minor complication that saturated pixels may have values slightly less than this maximum. This effect is easily addressed, however, by using a lower, more conservative threshold to detect saturation [6,8].

Saturation is caused by underlying physical characteristics of the sensor which limit the highest irradiance that can be measured for the given settings of the camera. In a digital sensor, where incident photoelectrons are recorded as electric charge, each sensor element can store a maximum amount of charge known as the *full well capacity*. Together with the exposure time and amplifier gain, the full well capacity imposes a limit on the maximum irradiance that can be measured before saturation. Film-based sensors are subject to saturation as well, but the mechanism limiting their photo-sensitivity is chemical [9].

While modern digital sensors are designed to dissipate excess charge above the full well capacity, for very bright parts of the scene, excess charge from a saturated pixel can spill over to adjacent regions. This artifact, known as *blooming*, can lead to saturation in pixels that would not otherwise be saturated.

Application

Saturation can pose problems for computer vision algorithms that assume linearity unless saturated pixels are identified and handled appropriately. For example, methods operating in the Fourier domain require special attention to saturation [1,18], because the global nature of the transform means that even isolated saturated pixels can corrupt the whole image. The two main approaches to dealing with saturated pixels are explicitly treating them as missing values and interpolating them from surrounding pixels.

The effect of saturation should also be taken into account when estimating the parameters of sensor noise from an image [11,5]. Pixels near saturation will demonstrate reduced variance in general, since the maximum value imposed by saturation will make their samples closer on average.

From the standpoint of photography, camera settings should be chosen to avoid saturation in regions of interest, otherwise important detail or color information may be lost. Photographers describe saturated images as being *overexposed* or as having clipped or blown highlights. Although ill-posed, a problem of great practical interest to photographers is recovering detail in saturated regions of the scene, or at least hallucinating plausible detail.

Under mild overexposure, only partial color information may be lost due to saturation. Partial saturation results from the different spectral sensitivities of each color channel, leading one channel to saturate before the others. In this setting, the main approach for restoring detail is to represent the correlation between color channels, using either global [19] or spatially-varying [12,7] color distribution models, then using this correlation to transfer information from the non-saturated color channels.

With greater overexposure, pixels become saturated in all color channels. The most common approach for restoring detail in this setting is to blindly extrapolate smooth peaks within saturated regions [15,17,7]. In fact, saturated regions can sometimes provide quantitative evidence about the underlying irradiance. Provided that overexposure is moderate and the scene is sufficiently smooth, the band-limitation of irradiance [1] or the resulting noise distribution [4] can be exploited to recover detail in fully saturated regions. For more severe overexposure or larger saturated regions, none of these methods are generally sufficient. In such cases, user guidance may be enlisted to help transfer plausible high-frequency detail from other sources [17].

In general, choosing the exposure setting for a photo requires balancing competing goals. While overexposure causes loss of detail in the highlights due to saturation, underexposure leads to higher relative noise. The relationship between noise and saturation defines the *dynamic range* of the sensor and determines the range of irradiances that can be captured acceptably in a single shot. When restricted to a single shot, one should generally choose the exposure setting so that the brightest region of interest falls just below the saturation point [14].

For scenes with large dynamic range, such considerations have motivated *high dynamic range imaging* methods based on capturing multiple photos with different exposure times [3], each of which saturates at a different irradiance. There is also an ongoing effort to develop new kinds of high dynamic range sensors offering higher effective saturation levels [10]. A broad range of new designs have been proposed, including sensors that record the precise length of exposure time needed to reach saturation and sensors with a logarithm-like response. Each of these designs present unique tradeoffs, including different noise characteristics over their operating range [10]. An orthogonal imaging approach is to use spatial multiplexing to incorporate multiple types of sensor elements, each having different sensitivities [13,18] or sizes [16].

Recommended Readings

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