How to Measure a Camera's Response Curve from Scratch*

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Abstract

This paper describes how the response curve of a video camera can be determined with the aid of a sheet of paper and two desk lamps only. The calibration process is based on the superposition law of incoherent light and does not make use of any calibrated measurement instrument.

1 Introduction

Digitizing and processing of video images has steadily gained importance in recent years. Various applications profit from this technique, in particular industrial inspection, optical measuring, desktop publishing, and remote sensing. For applications which are sensitive to image quality an exact characterization of the properties of the data acquisition equipment is essential. Knowing the equipment's response curve is especially important because many applications either rely on a linear response curve or on a specific power law (γ-correction).

Relying on the data sheets of the measurement equipment is only partially useful because

1. The data is often missing (*e.g.* for the digitizer).
2. The data sheets may be incomplete, inaccurate, or even erroneous.
3. The measurement equipment as a whole (*i.e.* camera plus digitizer) may react in a way that is not expected from the individual parts, *e.g.* due to undesired feedback.

Calibrating the system with the aid of a calibrated measurement instrument is the standard procedure. In some situations, however, the user would like to be completely independent of any other measurement instrument because

1. He does not trust the calibration instrument, which may be imprecise or even broken.
2. Calibration instruments are expensive.

This paper presents a measurement method which provides precise calibration results and only relies on equipment that is readily available in any laboratory or factory: the system we want to characterize (*i.e.* a camera, a frame store, and some computer), two light sources (desk lamps or spot lights), and a sheet of uniformly white or gray paper.

The proposed method bases on the additivity of incoherent light (Section 2) and on the fact that various sets of light sources easily can be adjusted such that an *equal* system respons results (Section 3), even if the exact response curve is not yet known.

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2 Additivity of light

According to the theory of optics, the illuminance from two independent and incoherent light sources equals the sum of the illuminances from the individual light sources [1]. Illuminance is defined as the amount of light received on a unit area of a surface. In addition, for common light sources (from candles to floodlights but not necessarily for a collimated laser beam) the amount of light (luminance) re-emitted from an illuminated surface is almost perfectly linear with respect to the illuminance of the incidenting light, whereas the angular distribution of the re-emitted light is independent of the illuminance. Deviations from this "principle of linearity" [2] are not noticeable in practice.

Each piece of illuminated surface, due to its re-emittance of light, again acts as a light source which, in good approximation, can again be considered incoherent and independent with respect to other surface elements.

Taking these properties together we find the following principle of incoherent light superposition, which forms the basis of any ray tracing algorithm in computer graphics [3]:

Let $I_s(I_1) = \alpha_1 I_1$ be the illuminance of a particular unit surface, directly and/or indirectly illuminated by a light source L_1 with luminous intensity I_1 and let $I_s(I_2) = \alpha_2 I_2$ be the illuminance of the same unit surface, directly and/or indirectly illuminated by a light source L_2 with luminous intensity I_2. The coefficients α_1 and α_2 are constant factors, depending on the relative positions of the light sources and on the geometry and reflectance properties of the scene. Then the principle of incoherent light superpostion specifies that the illuminance for a simultaneous illumination with the light sources L_1 and L_2 equals:

$$I_s(I_1, I_2) = I_s(I_1) + I_s(I_2) = \alpha_1 I_1 + \alpha_2 I_2 \tag{1}$$

This superposition law holds irrespectively of the properties (*e.g.* diffuse vs. specular) of the surfaces composing the scene and irrespectively of mutual reflections. In our camera calibration experiment, in particular, each individual camera pixel forms a unit surface for which the principle of incoherent light superposition applies.

3 Measurement procedure

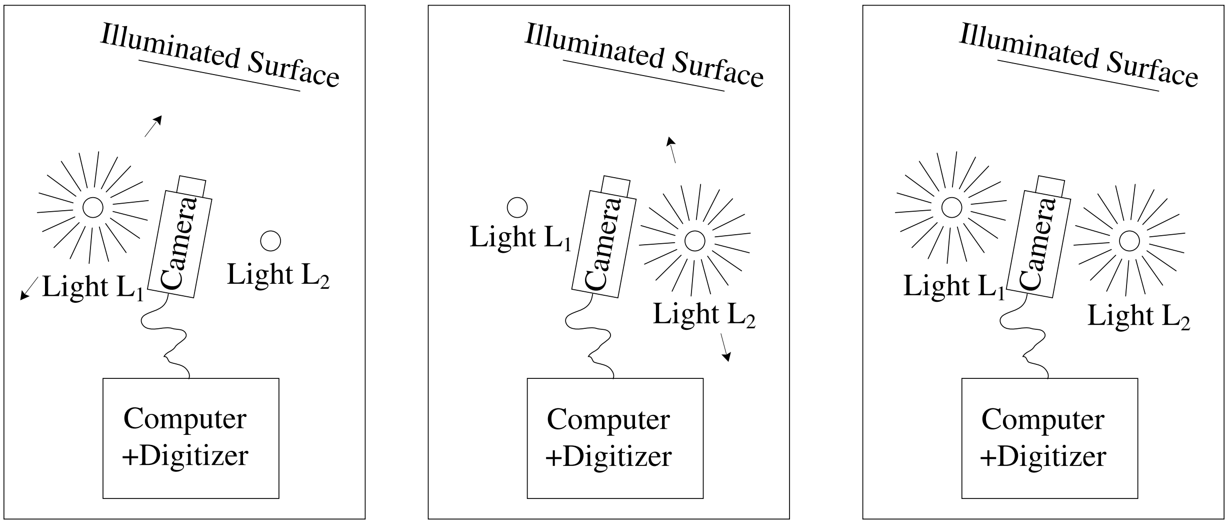
As outlined in the previous section we want to use the principle of incoherent light superposition for each individual pixel. In order to accomplish this goal we take a sheet of uniformly white or gray paper and look at it with the camera. Additionally we take two spotlights or desk lamps that we can switch on and off independently and direct the light spot onto the paper, illuminating it uniformly. Uniform illumination is not critical for the measurement procedure but helps to reduce error sources.

If both lights are switched off, the room has to be completely dark (at least as dark that putting the light protection cap onto the camera lens does not alter the video signal).

Let us look at a particular pixel with coordinates (i, j). The illuminance of this pixel is proportional to the luminance of the surface element the camera is looking at. The following procedure can be used to estimate single pixel response curves $r(I)$ for this pixel, where r is the measured digitized value and I is the illuminance of the camera pixel. The pixel illuminance I will finally be known up to a multiplicative constant and is therefore expressed as:

$$I = f \cdot I_{ref} \tag{2}$$

where the reference illuminance I_{ref} is defined by directing the camera onto a surface element with a particular reference luminance, and where f is a dimensionless factor.



(a) (b) (c)

Figure 1: Sketch of the measurment setup. (a) Light L_1 is switched on and adjusted to get a desired system response. (b) Light L_2 is switched on and adjusted to get the *same* system response. (c) Lights L_1 and L_2 are switched on and the system response of the doubled illumination is measured.

In order to simplify the discussion let us first assume that the system response is noiseless and precise up to arbitrary many digits. The measurement procedure takes the following form:

1. Determine the black level by switching off both lights and measuring the system response for the pixel, thus measuring $r(0)$.

2. Define a unit illuminance level I_{ref}, *e.g.* by positioning a light source such that $r(I_{ref}) - r(0) = 1$. All subsequent measurements will be relative to this reference illuminance, so that the final response curve will be known up to a multiplicative constant, depending on the absolute reference illuminance.

3. Iteratively determine the response for $r(2^k \cdot I_{ref})$ with a series of measurements:

   (a) Adjust light L_1 and light L_2, by turning a dimmer or altering the distance, such that, when switched on individually, each light shows a response $r(2^k \cdot I_{ref})$, starting with $k = 0$, *i.e.* the reference illuminance (Figure 1a and 1b).

   (b) Switch on both light sources together (Figure 1c), thus determining $r(2^{k+1} \cdot I_{ref})$ based on the assumption of incoherent light superposition.

   (c) Repeat a) and b), incrementing k, until the maximum system response is reached.

4. Iteratively determine the response for $r(f \cdot I_{ref})$ with a series of measurements where f is any integer number, by subsequently splitting the interval between $2^k \cdot I_{ref}$ and $2^{k+1} \cdot I_{ref}$:

   (a) Adjust light L_1 and light L_2 such that, when switched on individually, the response of light L_1 is $r(f_{1m} \cdot I_{ref})$ and the response of light L_2 is $r(f_{2m} \cdot I_{ref})$, starting with $m = 1$, $f_{11} = 2^k$ and $f_{21} = 2^{k-1}$.

   (b) Switch on both lights and thus measure $r(f_{1m+1} \cdot I_{ref} = (f_{1m} + f_{2m}) \cdot I_{ref})$. Increment m.

(c) Repeat a) and b) using as f_{1m} all measurements obtained so far and $f_{2m} = 2^{k-m}$, until a desired precision is reached.

Starting with a sufficiently small I_{ref} the relative response for any desired I can be measured with the above procedure. Once we have measured a number of points we can, at any point of the calibration procedure, replace additional measurements by interpolation. The interpolation error depends on the complexity of the response curve between the measured points and is expected to become small for a moderately small sampling distance.

For a single measurement the precision of r is limited by the precision of the digitizer, *i.e.* limited to integer values. If, however, we repeat the measurement many times and average the results, as discussed in the next section, an arbitrary precision can be reached.

As an example, let us determine the system response $r(6 \cdot I_{ref})$, assuming that $r(0, i, j) = 6.1$ and that I_{ref} is defined by $r(I_{ref}) = 7.1$:

1. Individually adjust the two lights such that the corresponding illuminances I_1 and I_2 are given by $r(I_1) = 7.1$ and $r(I_2) = 7.1$, *i.e.* $I_1 = I_2 = I_{ref}$.

2. Switch on both lights. Assume that the measured system does not follow a linear law and that the response is 9.3 (instead of 8.1 for a linear system), thus $r(2I_{ref}) = 9.3$.

3. Individually adjust the two lights such that the corresponding illuminances I_1 and I_2 are given by $r(I_1) = 9.3$ and $r(I_2) = 9.3$, *i.e.* $I_1 = I_2 = 2I_{ref}$.

4. Switch on both lights and assume that the measured system response is 17.4, thus $r(4I_{ref}) = 17.4$.

5. Adjust light L_1 such that $r(I_1) = 9.3$ and light L_2 such that $r(I_2) = 17.4$, *i.e.* $I_1 = 2I_{ref}$ and $I_2 = 4I_{ref}$.

6. Switch on both lights and assume that the measured system response is 22.8, thus $r(6I_{ref}) = 22.8$.

If, instead of a single pixel response, the average response curve for a group of pixels is desired then, in the procedure above, $r(I)$ for a single pixel has to be replaced by an average over the pixel group.

4 Possible modifications

The following modifications can help to improve the measurement precision and/or speed up the measurement process.

- The system response, in general, is noisy and can only be measured with the digitizer's precision. In addition, the light sources may fluctuate (for example due to the 50Hz or 60Hz of the alternating current supplying the light sources). These effects can be reduced by $\sqrt{N_{meas}}$ if N_{meas} subsequent measurements are taken. Averaging over a group of pixels is recommended if only the average response curve is of interest. If pixels are averaged, however, a homogeneous illumination becomes increasingly important.

- Instead of adjusting two light sources simultaneously we can also change the lens aperture.

- Assuming that each pixel shows the same response curve we can speed up the measurement procedure using two sheets of uniformly gray paper with different gray level. First we measure the relative luminance L_1/L_2 of the two sheets using the procedure of

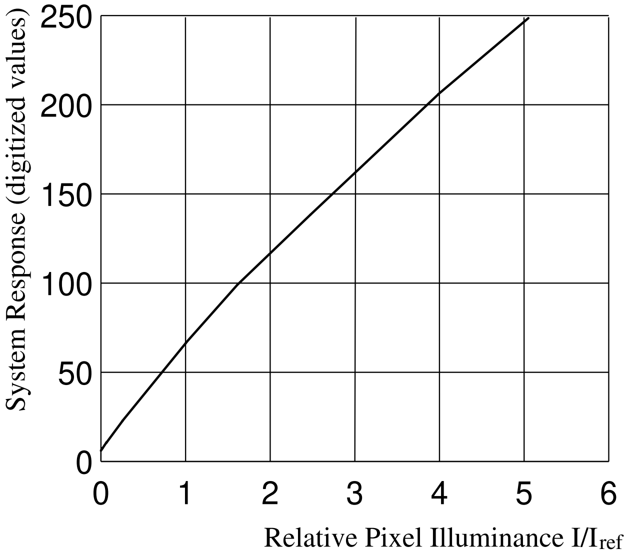


Figure 2: Measured mean response curve for a Sony XC-77CE CCD video camera plus a VisionLab frame store.

the previous section. With this knowledge we can quickly determine $r((L_1/L_2)^k \cdot I_{ref})$ for all k in the measurement range with the following procedure:

1. Place the two sheets of paper such that the camera is directed at both of them simultaneously.
2. Adjust light L_1 such that the system shows a response $r((L_1/L_2)^k \cdot I_{ref})$ for sheet S_1, starting with $k = 0$, *i.e.* with a known relative illuminance.
3. Measure the system response for sheet S_2, thus measuring $r((L_1/L_2)^{k+1} \cdot I_{ref})$.
4. Repeat 1) and 2), incrementing k, until the maximum system response is reached.

This last modification has the advantage that fluctuations of the light source cancel out in the calculations, because the system response for the two sheets of paper is measured simultaneously under the same lighting condition.

5 Experiment

A Sony XC-77CE High resolution CCD video camera together with a Silicon Graphics VisionLab board was tested with the above procedure. The result is shown in Figure 2 and shows a nearly linear mean system response. This result is as expected since the response curve of the video camera is linear according to the official data sheets and since the digitizing board should show a linear response to the video signal. The mean video offset (system response to darkness) equals 5.2.

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