RELIABLE MEASUREMENTS OF POFs' OPTICAL PROPERTIES WITH A LOW-END CCD CAMERA

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Abstract: *CCD camera can be fast and robust instrument for POF measurements, especially compared to scanning techniques. However, most of reasonably priced cameras are constructed to give more qualitative than quantitative results. We discuss common CCD cameras' inaccuracies and calibration procedure. (CCD camera, POF measurement, calibration)*

1. Introduction

Most of the traditional measurement methods of such POFs' optical properties as far and near field are either time-consuming (as scanning techniques) or require expensive instruments (as goniophotometers or high-end scientific area scan cameras). On the other hand, there are many fast and reasonably priced low-end CCD cameras, but they introduce a number of inaccuracies that make obtaining meaningful quantitative results difficult.

However, it is possible to make POFs measurements with a low-end CCD camera more reliable. In this paper we discuss most common inaccuracies of such cameras (paragraph 2), propose calibration procedure based on individual cells calibration (paragraph 3) and address common problem of too small bit depth (paragraph 4). Sample calibration data obtained for DALSA's 8 bit CA-D4 camera [1] and a sample calibrated POF measurement are presented in paragraphs 5 and 6, respectively.

2. CCD camera inaccuracies

Real CCD cameras introduce a number of inaccuracies into their measurements. Raw single CCD cell output n will be mathematically modeled as

$$n(m) = d + r(m) + e, \tag{1}$$

where m is the CCD cell's real excitation we like to measure, d is its constant bias (a result of its dark current), $r(m)$ represents its response function and e is its random noise variable. As d represents cell's bias at zero lighting intensity, response function $r(m)$ obeys

$$r(0) = 0. \tag{2}$$

As the whole CCD sensor is a matrix of CCD cells, three matrices of d, $r(m)$ and e parameters have to be considered for calibration purposes.

Note that response function $r(m)$ and random noise e in (1) may be wavelength-dependent. As the present study do not investigate their wavelength dependence, the calibration and final measurements should be made with the same light source wavelength.

In case of rapid lighting intensity changes between neighboring CCD cells a cross-talk effect may occur. While in most of POF measurements lighting intensity changes rather slowly with the angle, (1) does not include cross-talk effects.

2.1 Random noise

Random noise e of each CCD cell is a centered random variable (i.e. its mean is zero, $\mathrm{E}[e]=0$). A common way to estimate the influence of a random variable is through its sample standard deviation. Thus, to estimate the random noise we will make a series of T calibration measurements n_t under the same lighting conditions and compute the matrix of CCD cells' sample standard deviations s, where

$$s^2 = \frac{1}{T-1}\sum_{t=1}^{T}\left(n_t - \bar{n}\right)^2 \tag{3}$$

and $\bar{n}$ is an average of all n_t measurements. Note that as n depends on CCD cell excitement m, so may also s and above computation should be repeated for different lighting intensities and the maximal s value should be taken.

As a measure of a single measurement's uncertainty we will use $\pm 3s$ level (i.e. $\pm 3\sigma$ or 99.7% certainty level under normal distribution assumption).

Note that when the measurement is an average of M snaps, its uncertainty is less and becomes

$$\pm\frac{3s}{\sqrt{M}}. \tag{4}$$

Thus, the undesired effect of too high random noise may be easily reduced by averaging subsequent snaps.

2.2 Dark current

Non-zero dark current results in a non-zero bias matrix d of any CCD camera. It may be relatively simple measured, just by taking an average of a series of T measurements n_t made under completely dark conditions:

$$d = \frac{1}{T}\sum_{t=1}^{T} n_t \tag{5}$$

Note that, according to (4), an average of enough many T snaps should be used to diminish the influence of the random noise.

2.3 Response function

An ideal CCD sensor would have linear and identical response functions $r(m)$ of all its CCD cells. However, for a real CCD sensor cells' response functions may depend on the specific cell (non-uniformity) and be non-linear (intensity-dependence).

Slope coefficient $r'(m)$ of cell's response function is called cell's sensitivity. And normalized matrix of

$$\frac{r'(m)}{\bar{r}'(m)}, \tag{6}$$

where $\bar{r}'(m)$ is the averaged value of cells' sensitivities, will be called sensitivity profile of the CCD sensor (at lighting intensity m).

Note that the cells' sensitivity (6) may be (and usually is) non-uniform across the sensor due to the differences between cells' response functions $r(m)$, i.e. the sensitivity may be *position-depend*. Moreover, possible non-linearity of the response functions results in *lighting-dependence* of the sensitivity, as the slope of a nonlinear response function changes with lighting intensity m.

The obvious way to estimate $r(m)$ of a cell is: for every cell (a) measure few points on $r(m)$; (b) approximate measured points with a function that obeys (2).

Measurement of points $r(m)$ on the cells' response functions may be done in the following way:

- Use uniform lighting of CCD sensor (by using one distant light source or a big integrating sphere).
- Measure real lighting intensity (e.g. with a photodiode located next to the sensor). This is the common value of m (excitement co-ordinate) for estimating $r(m)$ for all the cells.
- Make a series of M snaps, compute an average measurement and subtract the sensor's dark current d, thus obtaining the matrix of
$$\bar{n} - d\ .$$
Those are the r co-ordinates of $r(m)$ points for all the cells.
- Repeat the above measurements with different values of m.

Special care should be taken when approximating $r(m)$ with a linear function, as even few percent of non-linearity may have a considerable effect on sensor's sensitivity profile.

2.4 Irregular cells

In a real CCD sensor not all cells are regular: some may be damaged or dead, response functions $r(m)$ of others may differ too much from an average or their random noise may be too high. All those factors make measurements of that part of CCD cells unreliable; we will call those cells *irregular*. Measurements of irregular cells should be approximated based on measurement results of neighboring cells.

Irregular cells may be located on basis of previously computed cells' calibration parameters, such as random noise and response function. As an example, the irregularity criteria for a cell may be as follow:

- Cell's random noise (4) is too big, i.e. it is greater than *mean* + 3σ of all cells' random noises.
- Mean square approximation error of cell's response function is greater than *mean* + 3σ or *r %* of all cells' mean square errors.
- Cell's response function differs too much from an average response functions (i.e. its coefficients fall outside the (*mean* $\pm$ 3σ) band of all response functions' coefficients).

3. Calibration

According to (1), real excitement m of a regular cell should be computed as

$$m = r^{-1}(n - d), \tag{7}$$

where n is cell's raw measurement. In fact, in order to minimize the effect of cell's random noise, in place of single measurement n in (7), an average $\bar{n}$ of M successive measurements should be used:

$$m = r^{-1}(\bar{n} - d). \tag{7a}$$

To decide on the number M of raw measurements to average, condition (4) should be considered. Note that as response function $r(m)$ of regular cells should be a monotonically increasing function, so should also be r^{-1} in (7) and (7a).

When real excitement of all regular cells is computed, excitements of irregular cells may be approximated by bilinear interpolation of nearest (in the same row and column) regular cells' excitements, computed previously with (7a).

4. Dynamic range

Bit depth of most of low-end CCD cameras is 8 bit, so their dynamic range is not better than 1:256. For many POF measurement applications it is not enough.

A simple solution (other than buying a costly high-end camera) may be as follow: (a) make several calibrated measurements with different exposure times; (b) scale down those made at longer exposure times using the least-square-error method to match the shortest exposure time measurement; (c) merge scaled measurements into final measurement. It should be kept in mind that:

- Downscaled measurements' absolute resolution increases with the exposure time (as their 3s levels are also downscaled), so it is better in low and worse in highly excited areas of the merged measurement. At most excited sensor areas it equals the resolution of the shortest exposure time original measurement (as this one is not downscaled).
- At long exposure times a blooming effect in highly excited areas may occur.

5. CCD camera example

DALSA's CA-D4 camera was used to obtain calibration data and a sample measurement according to the outlined procedure. The camera's technical characterization is:

- Bit depth: 8 bit, i.e. 256 gray levels.
- Pixel resolution: 1024×1024 cells.

Four series of 32 calibration measurements at 200 ms exposure time and uniform sensor lighting were made; the light source used was white, close to CIE standard illuminant A:

- 32 measurements under dark conditions with average raw excitation (dark current) of 8 gray levels and real lighting intensity 0.018 a.u.
- Three series of 32 measurements with average raw excitations of 30, 120 and 220 gray levels and measured real lighting intensities of 4.46, 20.10 and 35.70 a.u., respectively.

5.1 Random noise

The camera's average $3s$ level was found to be equal 2.4 gray levels and generally evenly distributed across the sensor (Fig. 1).

Thus, the 99.7 % certainty level (under normal distribution assumption) of a single measurement is ± 2.4 gray levels, what results in the dynamic range of about 5:256. It is considerably less that expected 1:256; random noise takes up 2 bits out of the camera's 8 bits.

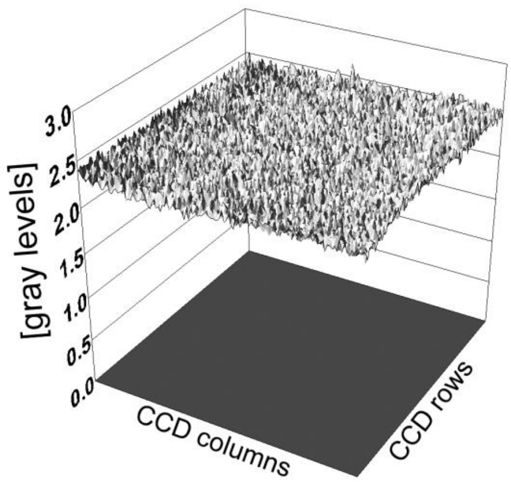

Fig. 1. Camera's $3s$ level at 200 ms exposure time.

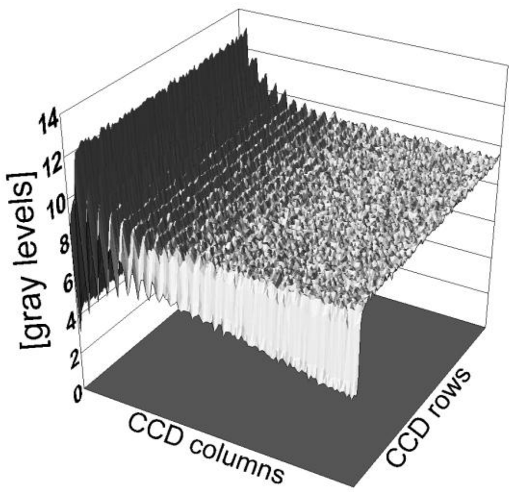

Fig. 2. Camera's dark profile at 200 ms exposure time.

5.2 Dark profile

An average of 32 raw measurements made under dark conditions was computed (Fig. 2).

Note that cell's average bias *d* can be as high as 12 gray levels, i.e. almost 5% of the maximum excitation (255 gray levels). On the left hand side of the sensor the dark profile is wave-like shaped; this is clearly the effect of the CCD cells' row arrangement.

5.3 Sensitivity profile

Four series of measurements result in four points on each cell's response functions. As linear approximations resulted in an average mean square error of 7%, the square function

$$r(m) = am^2 + bm \tag{8}$$

was used. Note that due to condition (2) there is no constant term in (8), it is characterized by the dark current d. By the use of (8) an average mean square approximation error was reduced to 2%.

Interpolated camera's sensitivity profile under dark conditions (i.e. (6) at m=0) shows that cells' sensitivity differences are as high as 5-6%.

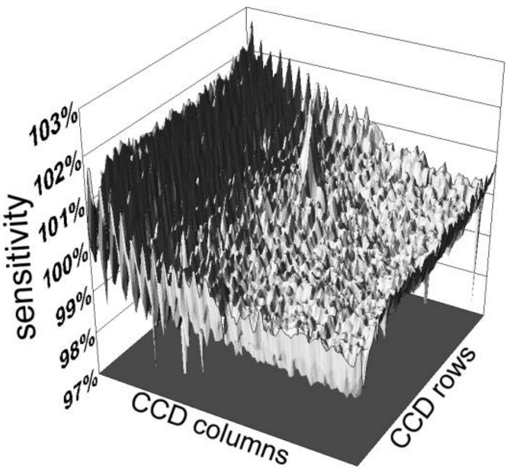

Fig. 3. Interpolated camera's sensitivity profile under dark conditions at 200 ms exposure time.

Note that camera's sensitivity profile at higher lighting intensities differs form Fig. 3, as cells' response functions (8) are non-linear.

5.4 Irregular cells

According to conditions from paragraph 2.4, camera's irregular cells were found. They are represented by black dots on Fig. 4.

Note vertical dot chains on the left hand side of the figure. They correspond to the wave-like structure on the left part of the dark profile (Fig. 2) and are due to the row arrangement of the CCD cells.

The number of irregular cells was found to be about 3% (30,000) of the total cell number (~1,000,000).

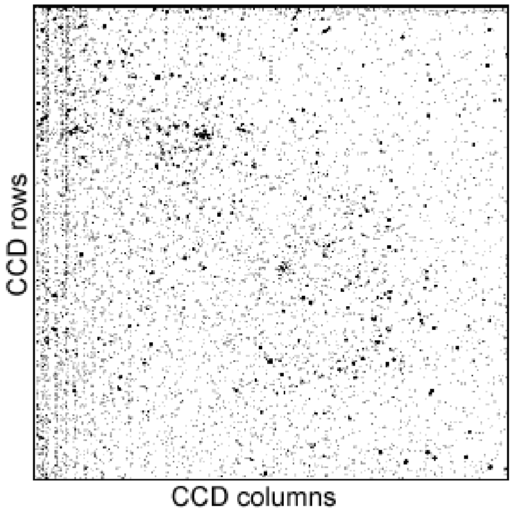

Fig. 4. Irregular cells. Due to representation limitations, the number of irregular cells seems to be higher than in reality (3 % of sensor area).

6. POF measurement example

For demonstration purposes two parallel POFs were used to illuminate the CCD sensor in a simple setup. The distances between fibers' end-faces and sensor were 15 mm and 5 mm, fiber lengths were 20 cm and 100 cm for fiber No. 1 and 2, respectively.

The calibration procedure described in previous paragraphs was repeated separately for five exposure times of the camera (50, 100, 200, 400 and 800 ms).

For each exposure time four snaps were taken to decrease random noise effect by a factor of two (according to (4)). Computed calibrated measurement was scaled to match the 50 ms measurement (Fig. 5).

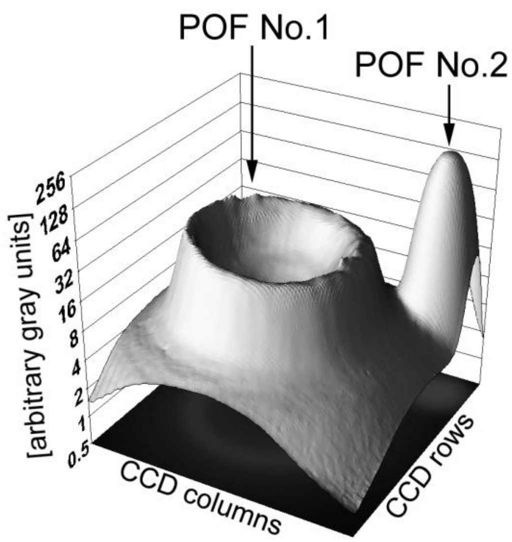

Fig. 5. Sample calibrated measurement.

Fiber No. 2 was lighted perpendicularly to its end face, so Fig. 5 shows only output of its lower order modes. As the lighting angle of fiber No. 1 was about 20°, light was transmitted through it only via higher order modes and a clear ring-like output pattern emerged.

Note that lighting axis still goes up to only 256 a.u., as it does with raw measurement at single exposure time. However, the advantages of applied calibration procedure are clear (see Table 1):

- Random noise 3*s* level is first decreased by a factor of two (averaging) and further by factors 2, 4, 8 and 16 for all but the most excited sensor areas (due to the downscaling effect).
- Due to less random noise, the absolute resolution was improved by the factor ranging from 27 (for low excited areas) to 2 (for most excited sensor areas).
- There is no effect of dark current.
- Irregular cells' measurements were interpolated.
- Measurement's non-linearity was decreased from 7% down to 2%.

Table 1. Summary of measurement improvements (GL = graylevels).

	Raw measurement at 200 ms	After calibration (best case)
Average dark current	8 GL	0 GL
Irregular cells	3%	Interpolated
Non-linearity	7%	2%
Random noise 3*s* level	2.4 GL	0.09 GL
Dynamic range	256 : 4.8	256 : 0.18

7. Conclusion

Common inaccuracies of a typical low-end CCD camera were discussed and a reliable calibration procedure was proposed. As presented procedure is easy to implement and considerably increases measurement reliability, it can be used for fast and reliable POF measurements besides its other applications.

Acknowledgements

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References

[1] DALSTAR CA-D4 Camera Product Info, http://vfm.dalsa.com/product_sel/prodInfo.asp?lbxProd__ID=CA-D4-1024

[2] NIST/SEMATECH, "Engineering statistics handbook", http://www.itl.nist.gov/div898/handbook/index.htm