

Methods for High Precision Shutter Speed Measurements

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Abstract—In this paper various methods are presented for measuring the shutter speed of cameras. Both classical methods for mechanical cameras and new methods for digital cameras are reviewed. Real measurements illustrate that the potential accuracy of novel methods is in the range of microseconds.

Keywords—shutter speed, exposure time, camera communication, equivalent sampling

I. INTRODUCTION

In VLC (Visual Light Communication) systems the information is transmitted as modulated light. On the receiver side photodiodes, phototransistors, or other light sensitive devices are used. Camera communication (CamCom) systems implement VLC with cameras as receivers. The overall performance of such a system is highly determined by the parameters of the camera, especially the shutter speed (or exposure time) [1]. On most cameras shutter speed can be set to given presets, measurement of the real exposure times are beneficial. This paper gives a review of different camera shutter speed measurements.

II. EXPOSURE TIME MEASUREMENT METHODS

A. Direct method

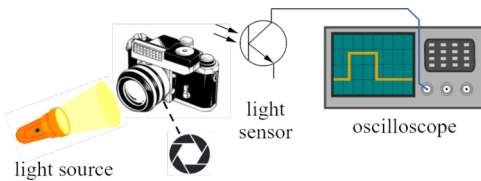


Fig. 1. Direct method using and oscilloscope.

In ISO standard 516 [2] a direct method is described to measure the shutter speed of either digital, or film cameras with mechanical, or electronic shutter. The described method uses the scheme shown in Fig. 1. The camera gets constant illumination through the lens and the light intensity is then measured behind the shutter with a photodiode or a phototransistor and an oscilloscope. The light sensor follows the change of the light intensity behind the shutter, the opening and closing events are visible as a rising and a falling edge

in the screen of the scope, making it possible to measure the time in between.

The solution is suitable for a wide range of cameras and shutter speeds, but unfortunately the disassembly of the camera is required to access the focal plane. Thus this method is only applicable during manufacturing and product testing.

The output signal of the light sensor clearly reveals the opening and closing events, and their difference gives a good estimate for the exposure time.

In [3] a good method is shown to measure the shutter time of film cameras replacing the film cartridge with the sensor. Unfortunately, in most digital cameras the focal plane is not accessible and the afore-mentioned procedures cannot be used.

B. Motion blur based methods

Other solutions take advantage of the mostly undesired phenomenon called “motion blur”. Here photos are taken of objects with known speed (see Fig. 2). The shutter time can be calculated from the shape of the covered area. The radial marker (green line in Fig. 2) forms a filled arc on the photo, from the angle and the angular speed the shutter time can be calculated.

The most common angular speed of a turntable is

$$\omega = 33\frac{1}{3} \text{ RPM} = 33\frac{1}{3} \cdot 60 \text{ RPS} = 33\frac{1}{3} \cdot 60 \cdot 360 \text{ DPS}, \quad (1)$$

where RPM and RPS mean Revolutions Per Minute and seconds, respectively, and DPS stands for Degrees Per Seconds.

Let be α be the central angle of the trace of on the photo taken of the turntable (green sector in Fig. 2). Then the exposure time $\hat{S}$ can be calculated as follows:

$$\hat{S} = \frac{\alpha}{\omega}. \quad (2)$$

Measuring α in the sub-degree range is difficult and exposure times longer than one revolution make the measurement ambiguous, giving this method a lower and an upper limit. Measurement range can be extended with variable angular speed. The detailed measurement method is described in [4] and further improved in [5].

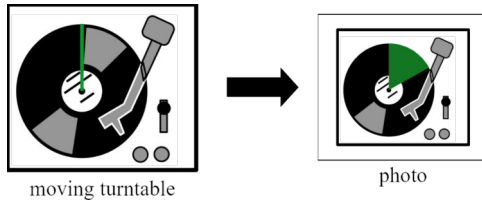


Fig. 2. Motion blur method with a turntable.

C. Virtual movement based methods

This measurement method uses the trace of the electron beam in a CRT (Cathode Ray Tube) screen as a virtually moving object. However the naked eye can see a still image on the monitor, only a small portion illuminates at once, as the electron beam scans through it.

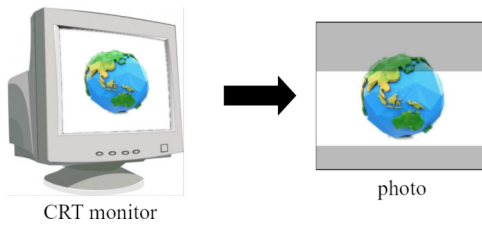


Fig. 3. Measurement using a CRT monitor.

The principle of the measurement method is shown on Fig. 3. The photo taken in the good moment from the monitor will contain a highlighted area, as shown in the right part of the figure. This is the part, where the beam hit the screen during the exposure. The most precise measurement can be achieved with this method, if the number of illuminated lines k is used instead of the area. Let be f_h is the horizontal sync frequency of the monitor. In case of standard 640×480 60 Hz VGA mode $f_h = 31.778$ kHz, determining the time of a single line to be $t_h = 1/f_h$. The exposure time can be calculate with the following formula:

$$\hat{S} = k \cdot t_h \quad (3)$$

More technical details can be found in [4]. The lower and upper bounds of the measurable exposure times are given by the time of a single line and the time of the entire screen. Instead of CRT monitors, alternatively the display of an oscilloscope can be utilized in a similar manner. In [6] a shutter speed measurement method is described, based on analog oscilloscopes.

D. “Running” LED based measurements

Replacing the physical movement with a logical one widens the possibilities in shutter speed measurement. In the setup shown in Fig. 4 an array of blinking LEDs is used, lighting up in series for equal times. From the the time of a single LED and the number of lit up LEDs on the photo the exposure time can be calculated. In [7] LED stripes of 100 LEDs are used, while the method [8] uses a 10×10 matrix.

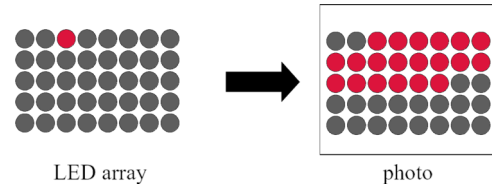


Fig. 4. Measurement device using an LED panel

The LEDs in the array light up after each other. Each LED is lit up for t_{LED} . A video frame showing k bright LEDs indicate an exposure time of

$$\hat{S} = t_{LED}k \quad (4)$$

Although this measurement method sounds straightforward at first, attention must be taken to the following conditions. First, the measurement device must be implemented so that turning on an LED and off the previous one must happen at the same time instant. Second, measurements can only be acceptable if there is at least video frame, where the illuminated LEDs are surrounded from both sides with at least one non-illuminated LED.

The experimental measurement device is based on a PIC16F876 microcontroller, running at 20 MHz clock speed, which drives 8 LEDs attached to the same 8-bit IO port, making it possible to manipulate the state of the 8 LEDs simultaneously, with a temporal resolution of $0.2\mu s$. With 8 LEDs exposure times between t_{LED} and $6 \cdot t_{LED}$ can be measured, in discrete steps. Extending the time, when one of the LEDs in the middle is turned on, extends the measurement range.

E. Equivalent sampling-based measurement

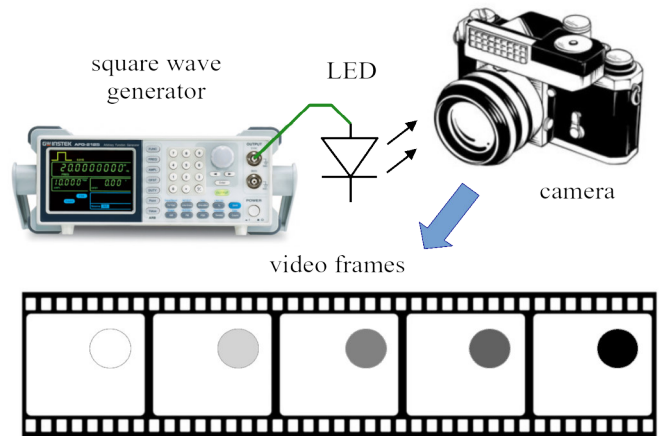


Fig. 5. The equivalent sampling-based method

The measurement setup, proposed in [9] is shown in Fig. 5. A square wave generator produces a square wave with 50% duty cycle, which drives an LED. Thus the light intensity $x(t)$ of the LED is a periodic square wave with period of P , as follows:

$$x(t + P) = x(t). \quad (5)$$

The camera takes a series of pictures (in video mode) of the blinking LED, where the sampling interval of the camera is T_S . The blinking signal's frequency is selected so that T_S is *almost* an exact multiple of P , as follows:

$$T_S = nP + \Delta t, \quad (6)$$

where n is any integer and Δt is much smaller than T_S . Using (5), for two consecutive pictures taken by the camera the following equations are true:

$$x(k) = x(t_k) \quad (7)$$

and

$$x(k+1) = x(t_k + T_S) = x(t_k + nP + \Delta t) = x(t_k + \Delta t). \quad (8)$$

Thus it seems that the second sample is taken Δt time after the first sample. This is the well-known equivalent sampling [10], and Δt is the equivalent sampling interval. The phenomenon of equivalent sampling is illustrated in Fig. 6.

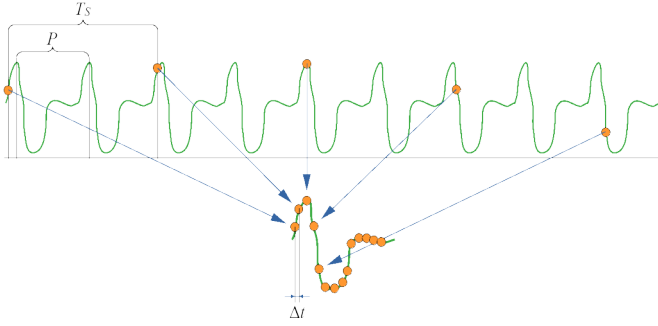


Fig. 6. Equivalent sampling of a periodic signal with equivalent sampling period of Δt

According to the camera sampling model [9], shown in Fig. 7, the sensor of the camera integrates the incoming light intensity during the exposure time S . The nonlinearity Γ models the saturation of the signal at high intensities. The sampled signal $x_S(k)$, measured around time instant t_k , is the following:

$$x_S(k) = \Gamma \left(\alpha \int_{t_k - \frac{S}{2}}^{t_k + \frac{S}{2}} x(\tau) d\tau \right), \quad (9)$$

where S is the exposure time and α is the gain of the camera. During the measurement, care is taken to operate the camera in a linear range, thus the output is the following:

$$x_S(t_k) = \alpha_0 + \alpha' \int_{t_k - \frac{S}{2}}^{t_k + \frac{S}{2}} x(\tau) d\tau, \quad (10)$$

The blinking signal's period is chosen so that the following constraint is fulfilled:

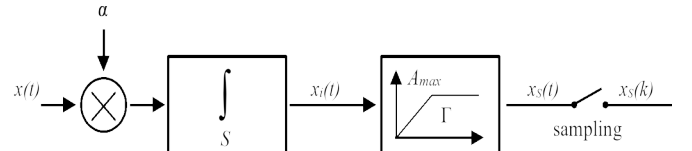


Fig. 7. Sampling model of the camera

$$\frac{P}{2} > S \quad (11)$$

In this case, since the input signal is a square wave, from (10) it follows that signal $x_S(t)$ is a trapezoid. The period length of $x_S(t)$ is P and the rising and falling times are equal to S , which is to be measured. Fig. 8. Illustrates the light intensity signal $x(t)$, while $x_S(t)$ shows the effect of integral sampling through time S , and $x_S(k)$ is the sampled version.

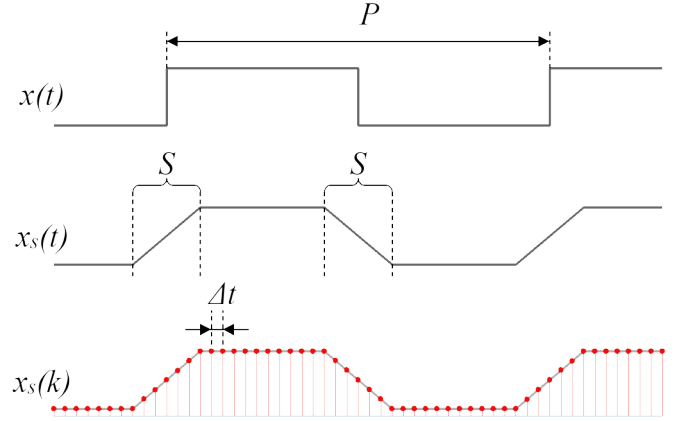


Fig. 8. The input square wave with period length of P , the integrated signal with exposure time of S , and the samples with equivalent sampling interval of Δt .

Let N_S be the number of samples in a rising edge of $x_S(k)$, and let N_P denote the number of the total samples in one period of $x_S(k)$, as shown in Fig. 8. The exposure time is estimated as

$$\hat{S} = \frac{N_S}{N_P} P. \quad (12)$$

In order to provide good resolution, small Δt values should be chosen: in this case the N_S and N_P become high. If Δt is high then values N_S and N_P are small and thus the resolution of $\hat{S}$ is poor.

The measurement procedure is the following:

- 1) The generator's period length is set according to (6). The camera is set so that the measured signal does not saturate the camera.
- 2) The generator's period length is fine-tuned so that the video output of the camera shows a slowly blinking LED. After tuning the period length P is read.
- 3) The video stream, containing the blinking LED, is recorded.

- 4) The intensity signal $x_S(k)$ of one pixel (e.g. the center of the LED) is extracted from the video.
- 5) The samples N_S and N_P are counted and the estimate $\hat{S}$ is calculated according to (12).

III. MEASUREMENTS

To illustrate the performance properties of the shutter speed measurement methods, two high-precision approaches were selected: a “running” LED-based and an equivalent sampling-based method were utilized. The tested device was a high quality industrial Grasshopper3 Color camera of type GS3-U3-23S6C, produced by FLIR [11]. The camera has an RGB color sensor, and it was used with 30 FPS frame rate and 8 bit image depth. The camera can be set to predefined shutter speeds between $5\mu s$ up to $31.9s$; in our tests six values in the range between $8\mu s$ and $1ms$ were utilized.

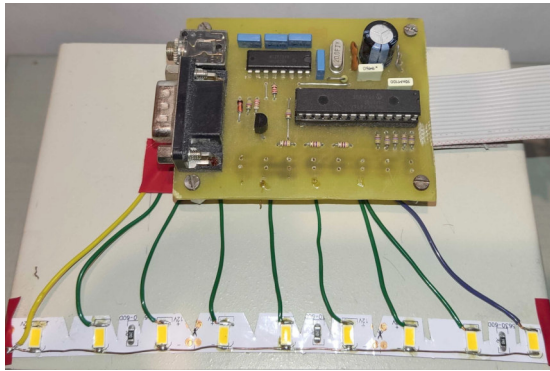


Fig. 9. Measurement setup for the “running” LED-based method

The running LED-based device is shown in Fig. 9. Here the LED pattern was generated by a PIC16F876 microcontroller board, driving 8 LEDs. The on-time of each LED was configurable individually with time resolution of $1\mu s$. The estimated accuracy of the device, originating from the resolution and the accuracy of the timer, was $\pm 1.5\mu s$. The basic operation principle is the same as in devices [8] and [9], but the smaller number of LEDs is compensated by the possibility of the individual configuration of each LED.

The equivalent sampling-based measurement setup is shown in Fig. 10. Here the square wave was generated using an Arduino Due board. The blinking frequency was chosen to be approximately 120 Hz (providing $P = 1/120s$), which is an integer multiple of the 30 FPS frame rate of the camera. The actual frequency was fine tuned in 5 millihertz steps.

The measurement results are shown in Table I. The nominal values were reported by the camera’s built-in software, the values $\hat{S}_{LED}$ and $\hat{S}_{EQS}$ are the measurement results by the “running” LED and the equivalent sampling-based methods, respectively. The two methods provide results within $1\mu s$. Interestingly, the camera shows a constant $6 - 7\mu s$ bias.

The operation of the equivalent sampling-based method is illustrated in Figs. 11 and 12. Fig. 11 shows a good measurement, where the camera operated in the linear operation range (color blue), while the other two measurements (red and

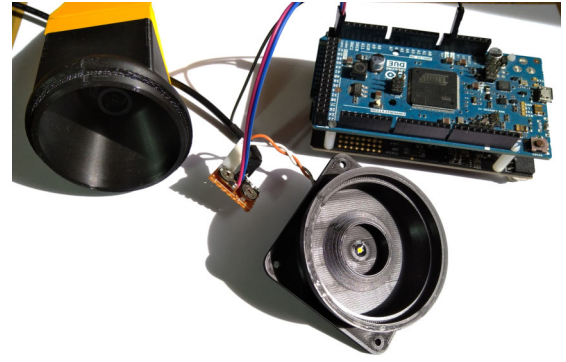


Fig. 10. Measurement setup for the equivalent sampling-based method: Camera with one half of the 3D printed cover (upper left corner), LED light source in center of half of the cover (bottom middle), Arduino Due as square wave generator (upper right corner).

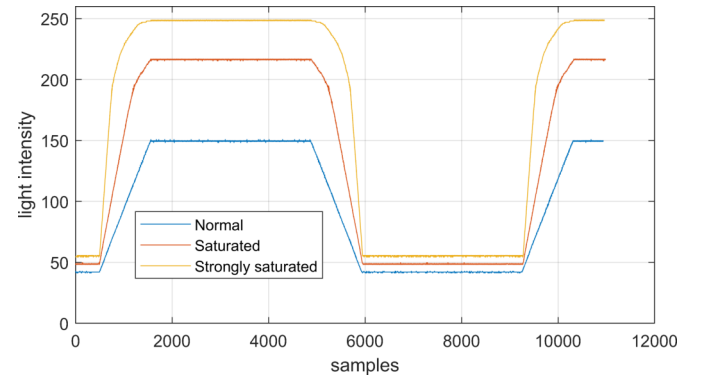


Fig. 11. Measurements with the tested camera taken in the linear range (blue curve) and with saturation (red and orange curves).

orange curves) show the effect of saturation. The trapezoid signal is apparent in the linear case, while it is distorted when the sensor is saturated, decreasing the measurement accuracy.

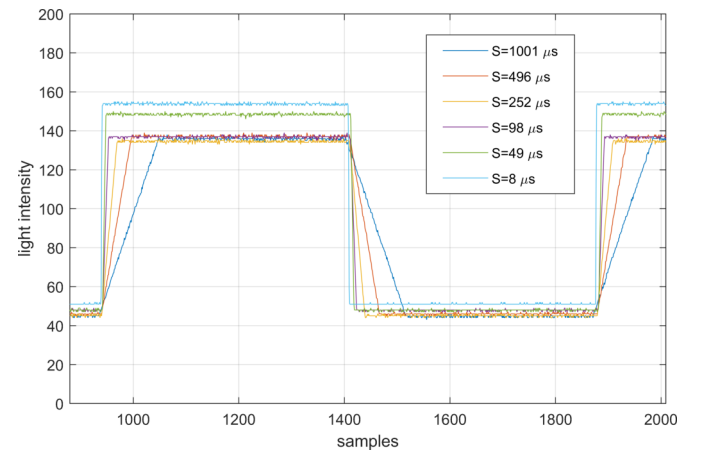


Fig. 12. Trapezoid diagrams of all measured exposure times of the camera. Legend shows the nominal S values.

In Fig. 12 measurements are shown with shutter speed values shown in Table I. All measurements were taken with the

same blinking frequency, thus the period length is the same for all cases. The length of the rising and falling edges are clearly different, and are proportional with the actual shutter speed.

TABLE I
MEASURED EXPOSURE TIMES WITH THE "RUNNING" LED
AND THE EQUIVALENT SAMPLING-BASED METHODS

Nominal $S(\mu s)$	f-stop	$\hat{S}_{LED}$ (μs)	$\hat{S}_{EQS}$ (μs)
1001	16	1008	1009.0
496	16	503	503.6
252	11	259	259.4
98	8	104	103.9
49	8	56	55.1
8	1.4	15	15.1

IV. SUMMARY

In this paper various methods were presented for camera shutter speed measurement. The operation principles were introduced for the direct, motion blur, virtual movement, "running" LED, and the equivalent sampling-based methods. The operation and performance properties of the latter two methods were also presented through the test of a high-end industrial camera. The measurement results indicate that these methods can provide accuracy in the low microsecond range.

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