A METHOD TO ESTIMATE PIXEL INTENSITY IN LINE SCAN CAMERA-BASED MEASUREMENT SYSTEMS USING EXPOSURE AND LIGHTING CONTROL SIGNAL CHARACTERISTICS

Zsófia Forgács
assistant lecturer, University of Miskolc, Institute of Automation and Infocommunication
3515 Miskolc-Egyetemváros, e-mail: zsofia.forgacs@uni-miskolc.hu

Abstract
The operation of machine vision control systems is greatly influenced by the lighting technology used. If the camera exposure signal and the LED pulse train come from different sources, their start times may not align. While matching the frequency of the exposure signal and the lighting control signal can enable full synchronization by adjusting the phase shift, in practice, the camera's sampling frequency and the lighting controller's signal frequency may differ, potentially leading to resonance effects and intensity variations in the captured images. To investigate this phenomenon and develop a compensating algorithm for frequency discrepancies, a procedure was devised to estimate the intensity resulting from the overlap of the signal curves.

Keywords: *line scan camera, exposure, illumination, LED control*

1. Introduction

The performance of machine vision-based control systems is significantly affected by the lighting technology employed (Ren et al., 2022). Line-scan cameras, with their smaller sensor area compared to traditional area-scan cameras, only capture one row of pixels per sampling cycle. Consequently, the geometric design of the lighting unit is not the primary consideration; a simple linear lighting positioned at the right angle in front of the target object can be suitable. However, a more crucial factor is the need for higher light intensity due to the short exposure times required (Steger and Ulrich, 2020), enabling the camera to collect sufficient illumination for the images.

The camera exposure signal and the LED illumination pulse train originate from distinct sources, consequently their starting times may not be synchronized (Sharma et al., 2021). When the exposure signal and the lighting control signal share the same frequency, their complete temporal overlap can be achieved by adjusting the phase shift of the latter signal (Plattner and Ostermayer, 2021). However, in practical applications, the sampling rate of the camera and the frequency of the signal from the lighting controller may diverge, which can potentially induce resonance and fluctuations in the recorded image intensity. To understand this phenomenon and for the subsequent development of the frequency difference compensating algorithm, a procedure was developed to estimate the pixel intensity resulting from the overlap of the signal curves for each pixel row based on two signals.

Line scan cameras only acquire a single row of pixels during each sampling cycle, and their sensor surface area is substantially smaller than that of conventional area scan cameras. Consequently, the geometry of the lighting unit is not the primary design consideration when developing the illumination system; rather, a simple line lighting solution positioned at the right angle in front of the target object will suffice. A more critical factor is that due to the short exposure duration, the camera requires a higher light intensity to capture sufficient illumination for image formation.

LED light sources are extensively used in industrial machine vision systems owing to their extended lifespan, low power consumption, and rapid response time (Gilewski, 2023). These light sources can be operated using several control methods (Ribas et al., 2019), either with constant voltage or a pulse train. The advantages of constant voltage control include its simplicity and reliability, as no specialized control or timing is necessary. The brightness of the LED depends directly on the voltage and setting the appropriate light intensity is also easy. However, the continuous load under constant voltage operation can generate heat, potentially reducing the LED’s lifetime.

The utilization of pulse control with LED light sources entails the delivery of brief yet intense flashes of illumination. The pulse train must be synchronized with the camera’s sampling frequency to ensure proper detection of the illumination. This approach offers the advantage of prolonging the LED’s lifespan, as it is only activated for a short duration, thereby generating less heat. Pulse train control enables precise regulation of the exposure duration during the camera’s exposure period, potentially resulting in better image quality. Additionally, by manipulating the pulse sequences of the LED light sources, the light intensity can be adjusted through modifications to the pulse width.

The illumination frequency is a critical factor in capturing high-quality recordings with line scan cameras. These cameras typically operate at a high line rate, necessitating a correspondingly elevated illumination frequency to ensure that sufficient light reaches the sensors during each recording. To achieve proper synchronization and clear imaging, the illumination frequency must be equal to the camera's line rate.

Most industrial cameras can indicate the active exposure time during image capture. This information enables synchronizing the lighting with the exposure period. When the exposure is active, it can be triggered or regulated at the appropriate time to ensure the captured images meet the required quality standards (Wang et al., 2022; Zhang et al., 2022). The camera used in the research has 3 digital inputs and 2 digital outputs, which provide symmetrical transmission lines according to the RS-422 standard. This symmetric serial communication protocol ensures high reliability and robust noise-free data transmission (Ajtonyi, 2008). Differential signaling enhances immunity to electromagnetic interference, a crucial capability in industrial settings prone to such interference effects.

The camera’s digital output is leveraged for lighting control, with the output signal received by a control circuit that uses this information to regulate the LED light source. A circuit governed by an RS-422 signal controls the LED’s illumination, synchronizing it with the camera’s exposure period. This solution offers several advantages. Utilizing the camera’s digital output facilitates precise synchronization with the exposure period, which in turn enhances the accuracy and reliability of image processing. Furthermore, the RS-422 standard’s high-reliability differential serial communication enables dependable signal transmission over extended distances, a particularly beneficial feature in industrial settings.

For lighting control with I/O lines, the “Exposure Active” output signal was used, which switches to a high signal level at the beginning of the exposure and to a low signal level at the end of each row of pixels. The lighting setup employed a linear arrangement of three 10-watt LEDs connected in series. To control the lighting system, a MOSFET-based circuit was constructed. Notably, the RS-422 data required conversion into a unipolar, binary signal sequence prior to control. To facilitate this, a conversion module equipped with the necessary communication circuit elements, including 120-ohm terminating resistors, was utilized.

The traditional lighting control approach utilizing camera I/O lines has a limitation in that it generates the pulse sequence required to regulate the light sources based solely on the exposure signal, without providing feedback regarding the recorded and processed image data. Furthermore, to utilize RS-422 lines, an additional signal conversion circuit must be installed.

The purpose was to develop an alternative lighting approach that allows for the feedback of image data, enabling the control of LED light source signals. To evaluate the lighting later, a solid-coloured, non-patterned test sheet was monitored using a camera. Inadequate lighting during a recording period manifests as a row of darker pixels in the captured image, as illustrated in *Figure 1*.

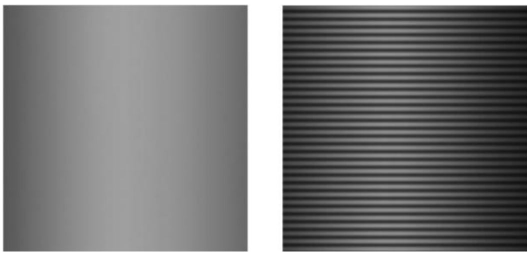

Figure 1. *Effect of LED lighting controlled by constant voltage and pulse train on recordings*

The images were captured with a line update frequency of 51 kHz. For the left-hand recording, the lighting unit was controlled using a constant voltage. In contrast, the right-hand recording employed a 50 kHz pulse series to control the LED circuit, with the pulse input provided by an FPGA.

Precise synchronization of pulse control is critical. The presence of a striped pattern suggests that the pulses and the camera's exposure intervals are not properly aligned. This mismatch frequently arises when the LED pulse frequency and the camera's line rate are not equivalent. If the pulse frequency does not appropriately correspond to the camera's sampling frequency, the consequence may be a striped pattern on the image, which diminishes image quality. In the following chapters, the characteristics of the two signals will be examined and the development of a simulation algorithm based on this examination will be presented.

2. Examination of exposure and lighting control signal characteristics

The camera's exposure signal and the LED pulse train originate from disparate sources, which means their initiation times may not coincide. To ensure synchronization between these two signals, the potential for phase shifting the LED pulse sequence is necessary. By applying phase shift, the starting point of the pulse train can be adjusted to better align with the camera's exposure signal, thereby maximizing the overlap and guaranteeing proper timing. This phase shifting mechanism allows for fine-tuning the timing relationship between the camera's exposure and the LED pulse train, ensuring that the LED illumination is precisely synchronized with the camera's image capture, which is crucial for achieving optimal image quality and accurate data acquisition.

The function $f(t)$ represents the camera's active exposure time, and the function $g(t)$ represents the LED's turn-on pulse sequence. The definitions of these two functions are then provided.

$$f(t) = \begin{cases} 1, & if\ (t)\ mod\ T_f < D_f \cdot T_f \\ 0 & otherwise \end{cases}$$
$$g(t) = \begin{cases} 1, & if\ (t-\varphi)\ mod\ T_g < D_g \cdot T_g \\ 0 & otherwise \end{cases} \quad (1)$$

$where$:

T_f $[s]$: $period\ of\ the\ exposure\ signal$
D_f $[\%]$: $duty\ cycle\ of\ the\ exposure\ signal$
T_g $[s]$: $period\ of\ the\ LED\ control\ signal$
D_g $[\%]$: $duty\ cycle\ of\ the\ LED\ control\ signal$
φ: $the\ phase\ offset\ of\ the\ LED\ control\ signal\ compared\ to\ the\ exposure\ signal$

The active intervals (times of high signal levels) for n periods:

$$f(t): \left[nT_f, nT_f + D_f T_f\right]$$
$$g(t): \left[nT_g + \varphi, nT_g + \varphi + D_g T_g\right] \quad (2)$$

The overlap interval of the two curves within one period can be given by the intersection of f and g:

$$O(f,g) = \left[nT_f, nT_f + D_f T_f\right] \cap \left[nT_g + \varphi, nT_g + \varphi + D_g T_g\right] \quad (3)$$

The overlap times within a period:

$$t_O = [t_{O1}, t_{O2}] = \left[\max\left(nT_f, nT_g + \varphi\right), \min(nT_f + D_f T_f, nT_g + \varphi + D_g T_g)\right] \quad (4)$$

The length of the overlap interval within N periods:

$$I_O = \sum_{n=0}^{N-1} \int_{t_{O1}}^{t_{O2}} 1\, dt \quad (5)$$

Integral of the reference signal over N periods:

$$I_{ref} = N \cdot D_f T_f \quad (6)$$

For this, the following conditions must be met:

$$D_g \geq D_f$$
$$nT_g + \varphi \leq nT_f$$
$$nT_f + D_f T_f \leq nT_g + \varphi + D_g T_g \quad (7)$$
$$t_O > 0$$

The investigation focused on how the frequency and phase of the signals impacted the degree of overlap. The reference signal generated during the testing process was a square waveform with a frequency of 10 kHz and a duty cycle of 27.6%. The variable signal had a duty cycle of 50%. The data matrices that were examined are:

$Phase\ (°): X = \{\varphi_i \mid \varphi_i = i, where\ i = 0, 1, 2, \ldots, 360\}$

$Frequency\ (Hz): Y = \left\{f_j \mid f_j = j \cdot 100, where\ j = 0, 1, 2, \ldots, 1000\right\}$

$Overlap: Z = \left\{R_{ij} \mid R_{ij} = \frac{I_O(\varphi_i, f_j)}{I_{ref}}\right\}$

The results demonstrate that at a frequency of 10 kHz, with a minor phase shift, the overlap ratio is 1, as this matches the frequency of the reference signal. At 0 Hz, the lighting is controlled by a constant voltage, causing the LED to remain continuously illuminated, so the exposure signal coverage is independent of the phase shift and consistently exhibits a maximum value. Between 0–20 kHz, the variable signal more frequently overlaps the reference signal due to the higher duty cycle. *Figure 2* presents the overlap ratio as a function of frequency.

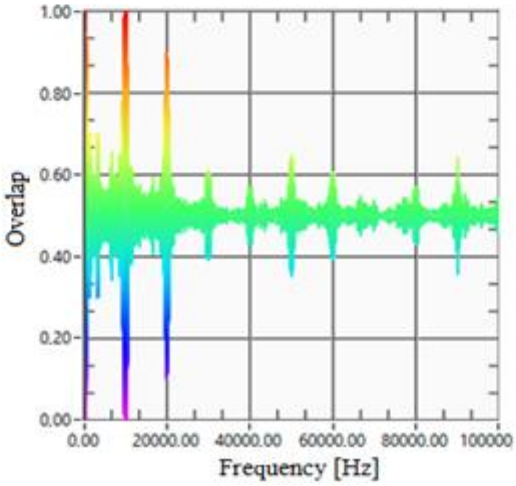

Figure 2. *The relationship between frequency and the overlap ratio*

For multiples of 10 kHz, the overlap values are greater compared to other frequencies, but they do not reach 1. In this scenario, multiple periods of the variable signal occur within a single period of the reference signal, and the overlap cannot be 100% due to the low signal amplitude during the half-periods.

The simulated square signals depicted in *Figure 3* have a consistent frequency of 5 kHz, with the filling factor for signal $f(t)$ at 27.6% and the filling factor for signal $g(t)$ at 40%. It is evident that the proper phase setting is also crucial for ensuring consistent lighting frequencies throughout the exposure period.

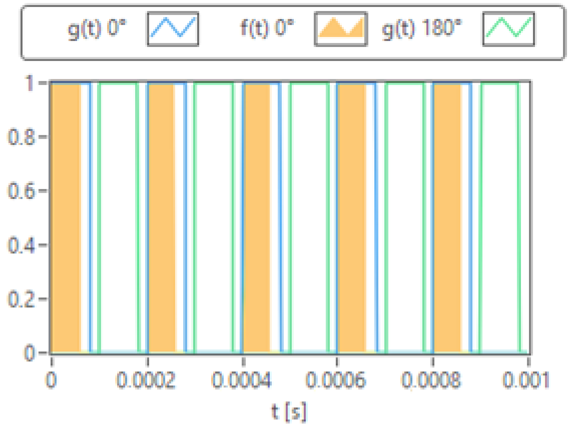

Figure 3. *The importance of phase shift during lighting control*

3. Simulation method to estimate pixel intensity based on the signal characteristics

If the exposure signal $f(t)$ and the lighting control signal $g(t)$ have the same frequency, the complete overlap of the two signals can be ensured by adjusting the phase shift of $g(t)$.

In practice, the camera's sampling frequency and the frequency of the lighting controller's signal may differ, which can lead to interference and fluctuations in the intensity of the recorded images. This phenomenon is illustrated in *Figure 4*, where a lighting reference signal of 20 kHz and a line rate of 20 kHz were set, but the discrepancy between the actual frequencies resulted in rows of pixels exhibiting varying intensity.

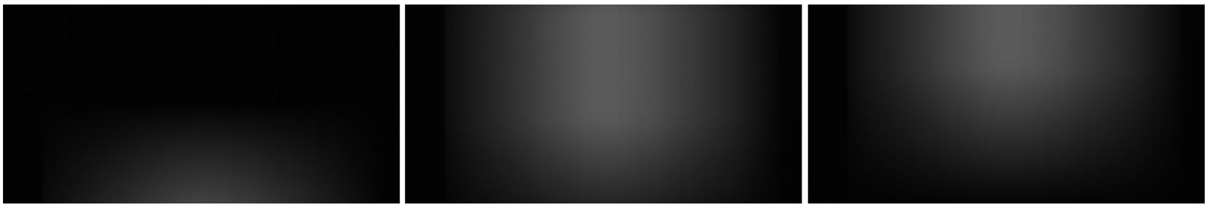

Figure 4. *Intensity changes due to frequency difference*

To understand the phenomenon and subsequently develop the frequency difference compensation algorithm, a procedure was devised to estimate the intensity resulting from the overlapping signal curves for each pixel row. This was based on the exposure signal $f(t)$ and the lighting control signal $g(t)$. For this purpose, I introduced the discrete time counterparts of signals $f[n]$ and $g[n]$, sampled at frequency f_s:

$$f[n] = \begin{cases} 1, if \ \left(\frac{n}{f_s}\right) mod \left(\frac{1}{f_f}\right) < D_f \cdot \frac{1}{f_f} \\ 0, otherwise \end{cases}$$
$$g[n] = \begin{cases} 1, if \ \left(\frac{n}{f_s} - \varphi\right) mod \left(\frac{1}{f_g}\right) < D_g \cdot \frac{1}{f_g} \\ 0, otherwise \end{cases} \quad (8)$$

To determine the overlap ratios between functions $f[n]$ and $g[n]$, it is necessary to quantify the number of sampling cycles during which both $f[n]$ and $g[n]$ exhibit high signal levels within the active period of $f[n]$. These values are stored in s_f and s_g for N samples:

$$s_f[0] = 0, \qquad s_g[0] = 0$$
$$\forall n \in \{1, 2, 3, \ldots, N\}:$$
$$s_f[n] = \begin{cases} s_f[n-1] + 1, & if \ f[n] = 1 \\ 0, & if \ f[n] = 0 \end{cases} \quad (9)$$
$$s_g[n] = \begin{cases} s_g[n-1] + 1, & if \ f[n] = 1 \land g[n] = 1 \\ s_g[n-1], & if \ f[n] = 1 \land g[n] = 0 \\ 0, & if \ f[n] = 0 \end{cases}$$

The expression for the vector O containing the overlap ratios is:

$$O = \begin{cases} O \cup \left\{ \dfrac{s_g[n-1]}{s_f[n-1]} \right\}, if\ f[n] = 0 \land f[n-1] = 1 \\ O, otherwise \end{cases} \quad (10)$$

Determining the number of elements of the vector O with an initial value of $k = 0$:

$$k = \begin{cases} k+1, \ \ if\ f[n] = 0 \land f[n-1] = 1 \\ k, otherwise \end{cases} \quad (11)$$

This represents the number of high signal level occurrences of function f within the active period for the given sample size.

$$k = \left\lfloor \frac{N \cdot f_f}{f_s} \right\rfloor \quad (12)$$

Based on the overlap ratio data of the vector O, a W wide $Q[i,j]$ image can be generated. This image is produced by illuminating a monochromatic surface with the control signal $g(t)$ at exposure $f(t)$, provided that the maximum intensity value available in the recording is I_{max}.

$$\forall i \in \{0, 1, \dots, W-1\}, \forall j \in \{0, 1, \dots, k-1\}: Q[i,j] = \lfloor O[j] \cdot I_{max} \rfloor \quad (13)$$

4. Results

An algorithm for estimating the pixel intensity has been implemented. *Figure 5* provides an example of how the algorithm works. The image on the left depicts the original recording, which was acquired at a line refresh rate of 10 kHz with 50 kHz LED illumination. If the base signal and the actual illumination frequency were identical, the resulting image would exhibit a uniform intensity, as the phase shift between the two signals would uniformly modulate the intensity values across the recording. The image on the right presents the outcome of the simulation, where the lighting control signal was set to 49.95 kHz in conjunction with the 10 kHz line update frequency.

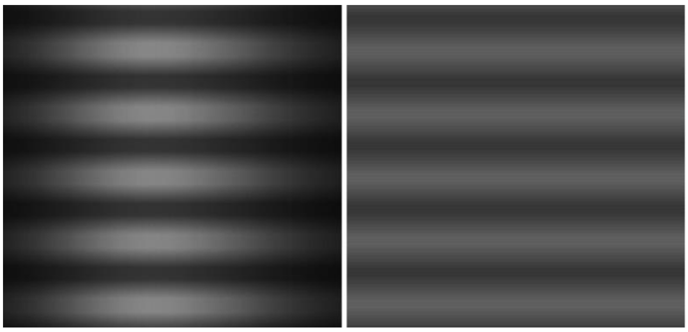

Figure 5. *Effect of frequency differences on the original and a simulated recording*

Even a minor (less than 1%) discrepancy between the set and actual frequency of the signals can result in a substantial, cyclic variation in the intensity of the recording, which is undesirable for subsequent processing operations. This periodic intensity change can negatively impact the quality and accuracy of the data analysis. It is therefore recommended to adjust the frequency setpoint of the lighting control system based on a careful assessment of the recordings to minimize this effect and ensure more consistent and reliable data for further processing.

5. Conclusion

The performance of machine vision-based control systems is significantly impacted by lighting conditions. Conventional lighting control systems that rely on camera input/output interfaces lack feedback on the image data. As a result, an autonomous lighting control system was developed, enabling feedback of the image data and regulation of the LED control signal. When the frequency of the camera exposure signal and the LED pulse sequence diverge, a resonance effect can manifest, leading to variations in the intensity of the recorded images.

A procedure has been developed to estimate the intensity of the recorded image, given the known characteristics of the exposure signal and lighting control signal. Subsequently, based on the simulation results, a method can be formulated to compensate for the frequency difference between the two signals, thereby mitigating the detrimental effects of disruptive periodic intensity variations. This method can be used to adjust the lighting control signal in a way that counteracts the resonance phenomenon, ensuring more consistent and stable image intensity throughout the operation of the machine vision-based control system.

References

[1] Ren, Z., Fang, F., Yan, N. et al. (2002). State of the art in defect detection based on machine vision. *Int. J. of Precis. Eng. and Manuf.-Green Tech.*, 9, 661–691. **https://doi.org/10.1007/s40684-021-00343-6**

[2] Steger, C., Ulrich, M. (2021). A camera model for line-scan cameras with telecentric lenses. *Int. J. Comput.Vis.*, 129, 80–99. **https://doi.org/10.1007/s11263-020-01358-3**

[3] Sharma, A., Raut, S., Shimasaki, K., Senoo, T., Ishii, I. (2021). Visual-feedback-based frame-by-frame synchronization for 3000 fps projector–camera visual light communication. *Electronics*, 10, 1631. **https://doi.org/10.3390/electronics10141631**

[4] Plattner, M., Ostermayer, G. (2021). Undersampled differential phase shift on–off keying for visible light vehicle-to-vehicle communication. *Appl. Sci.*, 11, 2195. **https://doi.org/10.3390/app11052195**

[5] Gilewski, M. (2023). Selective light measurement in the control of reference LED sources. *Sensors*, 23, 3285. **https://doi.org/10.3390/s23063285**

[6] Ribas, J., Quintana, P. J., Cardesin, J., Calleja, A. J., Lopera, J. M. (2019). Closed loop control of a series class-E voltage-clamped resonant converter for LED supply with dimming capability. *Electronics*, 8, 1380. **https://doi.org/10.3390/electronics8121380**

[7] Wang, Y., Chen, H., Zhang, S. et al. (2022). Automated camera-exposure control for robust localization in varying illumination environments. *Auton Robot*, 46, 515–534. **https://doi.org/10.1007/s10514-022-10036-x**

[8] Zhang, X., Tang, X., Yu, L., Pan, B. (2022). Automated camera exposure control for accuracy-enhanced stereo-digital image correlation measurement. *Sensors*, 22, 9641. **https://doi.org/10.3390/s22249641**

[9] Ajtonyi, I. (2008). Ipari kommunikációs rendszerek I. AUT-INFO Kft., Miskolc.