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LED flicker measurement: Challenges, considerations, and updates from IEEE P2020 working group

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Abstract

The introduction of pulse width modulated LED lighting in automotive applications has created the phenomenon of LED flicker. In essence, LED flicker is an imaging artifact, whereby a light source will appear to flicker when image by a camera system, even though the light will appear constant to a human observer. The implications of LED flicker vary, depending on the imaging application. In some cases, it can simply degrade image quality by causing annoying flicker to a human observer. However, LED flicker has the potential to significantly impact the performance of critical autonomous driving functions. In this paper, the root cause of LED flicker is reviewed, and its impact on automotive use cases is explored. Guidelines on measurement and assessment of LED flicker are also provided.

Introduction

In many applications, LED lighting has replaced traditional incandescent and fluorescent light sources, because of its low cost, high efficiency and design flexibility. In the automotive environment, LED lighting is now commonly used in vehicle headlamps, brake lights, reverse lights etc., and is also being used in traffic lights, advertising, speed signs, temporary road markings etc.

The brightness of LED lighting is often controlled by a combination of frequency and Pulse Width Modulation (PWM). By varying the pulse width (i.e. the duty cycle), the LED brightness can be varied. This is ultimately a much more efficient method of controlling illumination brightness than adjusting the analog current applied to the LED. This is because PWM dimming can achieve much higher dimming ratios than current modulation. Also, unlike current controlled dimming, PWM dimming does not cause a shift in LED colour.

In recent years, automotive cameras have evolved from simple backup cameras to advanced surround view systems, mirror replacement systems, and machine vision cameras that enable ADAS and autonomous driving. Automotive image sensors have also evolved at a rapid pace, from simple VGA resolution, to advanced, high resolution HDR sensors.

The simultaneous development of PWM driven LED lighting and the evolution of automotive imaging has led to the increasingly widespread phenomenon of LED flicker. LED flicker is an artifact observed in digital imaging where a light source or a region of an imaged scene appears to flicker (i.e. the light may appear to switch on and off or modulate in terms of brightness or colour), even though the light source appears constant when view directly by a human observer.

It should be noted that the term “LED flicker” has gained popularity, largely because of the widespread proliferation of LED vehicle lighting and road signage. However, the phenomenon does not occur exclusively with LED headlamps – any pulsed or low duty cycle light source will exhibit the same effect.

The implications of LED flicker vary, depending on the application. For simpler viewing applications (e.g. a rear view park assist camera), LED flicker may be considered as an annoyance or at worst a distraction for the driver. However for CMS (i.e. mirror replacement) cameras, flickering headlamps may be mistaken for turn signals/indicators or, as has been reported, may cause the driver to misidentify a following vehicle as an emergency vehicle. For machine vision based ADAS or autonomous driving applications, the consequences may be even more severe. LED flicker may cause misidentification of traffic signals, speed signs or safety messages.

In this paper, a brief overview of the root cause of LED flicker is provided. The implications of LED on various automotive use cases is explored. Guidelines on measurement and assessment of LED flicker are also provided.

Definition

LED flicker is defined as flickering or modulation in the luma and/or chroma within an image or video stream, even though the scene illumination would appear constant to a human observer.

It is important to distinguish between modulation of the light source and modulation within an image or video stream. A wide variety of illumination sources modulate, but do so at a frequency beyond the critical fusion frequency of a human observer. Hence, for the purposes of clarity within this standard, the terms “luminance modulation” and “illuminance modulation” refer to modulation of a light source, whereas “luma modulation” and “chroma modulation” refer to modulation within an image or video.

Root cause

The root cause of LED flicker has been explored extensively in the literature [1], [2], [3]. Briefly, LED flicker is fundamentally a sampling problem. LED flicker is in essence, a temporal sampling problem. It occurs when a light source is being powered by a modulated signal. LED lights may pulse several hundred times a second with varying duty cycle (percentage of the total time during which it is on) in order to adjust their apparent brightness. At these frequencies, the light will appear to be constant to a human observer, as the human eye effectively acts as a temporal low-pass filter. However, a camera imaging the light source may require a very short exposure time to capture a scene correctly, particularly in bright conditions.

An illustrative example is shown in Figure 1. In frame N, the camera exposure time coincides in time with a pulse from the PWM driven LED traffic light. Therefore, for frame N, the red traffic light will be captured by the camera. However, in frame N+1, the camera exposure time and LED pulse do not coincide. In this case, the red light will not be captured. Over the course of multiple video frames, the traffic light will appear to flicker on and off, depending on whether or not the camera’s exposure time coincides with the LED light pulses.

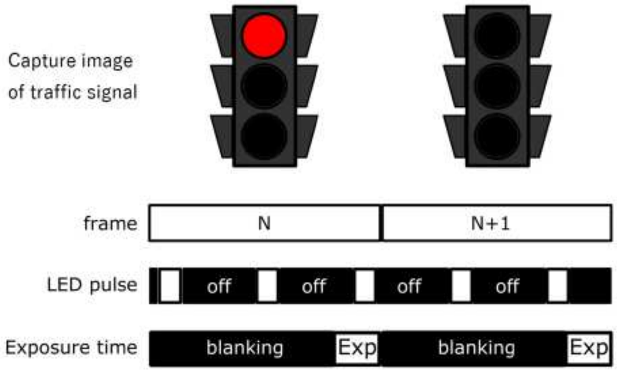

Figure 1. LED flicker root cause. In frame N, the LED pulse and the camera exposure time coincide, and the traffic light is captured. In frame N+1, the LED pulse and exposure time do not coincide, and the traffic light appears off

More specifically, a pulsed light source may flicker on/off if the exposure time of the camera is less than the reciprocal of the frequency of the light source i.e.

$$T_{exp} < \frac{1}{PWM_{freq}} * (1 - dutycycle) \quad (1)$$

Where T_{exp} is the exposure time of the camera, and PWM_{freq} is the frequency of the pulsed illumination.

In the following section, the various use cases and impact of LED flicker on automotive imaging applications are explored.

Use cases

There are two primary use cases of concern:

- Flickering or modulation in luma/chroma of a directly imaged light source within the field of view of a camera. Examples include flickering headlamps, traffic lights or road signs
- Flickering or modulation of luma/chroma of an area of the image illuminated by a PWM driven light source. For example, a road surface illuminated by a PWM driven light may appear to flicker or modulate in luma/chroma

It should be noted that in many scenes, a combination of both effects may occur simultaneously.

Flickering of directly imaged light sources

A directly imaged light source is a light source which is directly in line-of-sight of a camera. Most real world examples are localized to a relatively small region of an image; examples include headlamps, street lights, traffic signs, road markings etc.

Figure 2. Example of flicker from directly imaged light source. Two consecutive frames from a video sequence are shown. The sign is driven by a PWM signal. From frame to frame various letters in the sign appear and disappear

In this example, the LED running lights of the vehicle are driven by a PWM signal. The duty cycle and frequency of the LEDs are modified to dim the LED lights when the headlamps are activated. As a result, they appear to flicker when imaged by a camera. This figure illustrates a number of challenges with automotive lighting. Note, for example, that in this frame, the LED on the left appears off, while the LED on the right appears on. This quite typical. Most vehicles do not have any synchronization of headlamp frequency, duty cycle or phase between headlamps. The result of this is that headlamps typically flicker at different rates and/or phases.

Flickering within an area illuminated by a pulsed/modulated light source

Flickering may also occur when a scene is substantially illuminated by a pulsed light source. In this use case, typically a large area or the entire image area may be affected. A typical example would be where a scene is illuminated by a vehicle headlamp or streetlight which is driven by a pulsed signal. In this use case, the flicker artifact typically has both evident temporal and spatial characteristics. For example, if a rolling shutter image sensor is used, banding artifacts may occur i.e. dark or light bands across the image. An illustrative example is shown in Figure 3.

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Impact of PWM flicker

The impact and severity of flicker depends on the use case and application. For slow speed applications, including back-up camera systems or surround view systems, PWM flicker of light sources within the field of view will, in most cases, be mostly an annoyance or a distraction to the driver, because the driver will typically have enough time to assess the situation. However, there remains the possibility that the PWM flicker will distract the driver sufficiently to cause an accident.

Figure 3: Example of banding artifact. Images were captured with a 60fps camera. Examples were taken at different frequencies between 100Hz and 1000Hz. Unlike 50/60Hz AC banding effects, the number of bands, band height etc. can vary, depending on the frequency and duty cycle of the LED and the frame rate of the camera

There is a separate scenario that is also problematic for backup and surround view applications. If a vehicle has PWM driven reversing light, and is backing up into a parking space, it is possible that banding effects, as seen in Figure 3. This can be potentially quite disturbing to the driver, particularly when the banding frequency is high. An example of this phenomenon is shown in Figure 4.

Figure 4. Example of LED artifact in rear view and/or surround view applications. In this example, the headlamps of the vehicle are reflected on the wall in front of the vehicle. The reflect light appears to flicker in a visually disturbing manner

For high speed viewing applications, such as CMS (i.e. rear view mirror replacement systems), PWM flicker has a greater potential to cause accidents. As an illustrative example, consider the scenario where a vehicle has a CMS system, and the driver of this vehicle is viewing a vehicle following behind. The trailing vehicle is equipped with LED headlamps. It is common for vehicle LED headlamps to be driven by PWM signals with different frequencies and duty cycles. As a result, one headlamp may flicker at a slow rate (e.g. <0.1Hz), whereas the other headlamp may flicker at a faster rate (e.g. 0.5Hz). In this scenario, it may easily appear to a driver that the trailing vehicle has engaged their turn signal indicators. The driver may incorrectly assume the trailing vehicle intends to change lane or make a turn. This misinterpretation of the scenario has obvious potentially hazardous consequences. An example of this effect is shown in Figure 5.

In this example, the LED light highlighted appears to blink on and off with a frequency of ~0.5Hz, very similar to the frequency of a turn signal. The other LED light on the vehicle appears off for ~5 seconds in the video captured. The result is that, in this scenario, it appears that the vehicle's turn signal is on and the driver intends to change lanes. In reality, this was not the case.

Figure 5. Example where LED flicker creates the impression that a vehicle's turn signal has been activated.

Similarly, there have been anecdotal reports of drivers misinterpreting a trailing car for an emergency vehicle (e.g. a police car) with its warning lights on. This scenario can occur if the PWM driven lights flicker at a higher rate, e.g. 5Hz or greater. It has been reported that drivers changed lanes or made way for a trailing vehicle, under the false assumption that it was an emergency vehicle.

PWM flicker also has a potentially very significant impact on ADAS and autonomous driving applications. PWM LED lights are increasingly used for traffic signals and other traffic signs, including variable speed signs, road works signs etc. PWM flicker may cause misdetection or non-detection of traffic signs, again with potentially very hazardous implications.

This is shown clearly in the example in Figure 6. In this example, the traffic light is captured on and off in consecutive frames. This will cause significant challenges to traffic sign detection algorithms.

Emergency vehicles - Xe flashlamps

Another example of low duty cycle illumination is Xe flashlamps. Flashlamps are an electrical arc lamp designed to produce extremely intense light flashes for very short durations [4]. Xe flashlamps are used in emergency vehicle lighting, because they produce a very bright, eye-catching pulse of light for relatively low power input. However, because these flashlamps produce use a very short duty cycle, the light pulse they produce may be missed by the camera exposure, particularly in bright scenes. As a result, emergency vehicle lights may appear off to a camera system, when in reality they are pulsing. This can create obvious safety concerns.

HDR imaging

There are also specific artifacts caused by HDR imaging of pulsed light sources. A full description of the root cause of HDR LED artifacts has been described previously [1], [3]. Briefly, most HDR imagers in the automotive space use some form of multi-capture technique to extend dynamic range. When multi-capture HDR image sensors capture flickering LEDs, it is possible the LED pulse will be captured in one exposure, but not in another. As a result, the LED light can appear overexposed in one capture, and completely underexposed in another. When then these captures are merged, the result is a flat grey artifact, where no detail is preserved. An example of this is shown in Figure 7.

Figure 6. In this example, a traffic light flickers on and off in consecutive video frames

In this example, the sign on the bus is overexposed in the long exposure image, and underexposed in the short channel image. The merged HDR output is flat grey, with no detail. This image artifact can potentially cause misdetection or non-detection of traffic lights, turn signals, or other warning lights in the automotive environment.

Figure 7. Example of HDR PWM flicker in lowlight scene. The bus sign is driven by a PWM signal. In this frame, the bus sign is captured only by the long exposure and missed by the short exposure. The combined output is a mid-grey artifact with no detail.

LED Flicker mitigation

A full description of all techniques used to mitigate LED flicker is beyond the scope of this paper. Instead, a general overview of the approaches taken within the automotive application is provided.

The ideal automotive image sensor has a dynamic range of ~120dB, and is immune to LED flicker. To achieve this in theory, the exposure time of the sensor should be greater than the minimum frequency of the LED light being imaged. As per EN12966:2014, the minimum required frequency to avoid the appearance of flicker to the human observer is 90Hz. Therefore, the minimum required exposure time to avoid the appearance of flicker for a 90Hz light source is 11.111ms. In bright scenes, an exposure time of 11.111ms would cause an overexposed image in standard automotive cameras. Therefore, to mitigate LED flicker, a mechanism to extend exposure time without saturating pixels is required. Typically, this can be done in a number of ways, including extending the full well capacity of the pixel, reducing the sensitivity of the pixel, a "chopped" exposure approach [3], or a combination thereof.

Also, achieving 120dB from a single capture is beyond the capability of the current generation of image sensors. It is therefore necessary to employ some form of multi-capture technique to achieve 120dB. So to summarize, mitigating LED flicker at the image sensor and achieving 120dB requires a combination of technologies to extend the dynamic range, and to extend the time to saturation of the pixel.

As previously stated, there are a number of combinations of approaches currently feasible to achieve both high dynamic range performance and LED flicker mitigation. However, for some of these combinations, it is not necessarily possible to achieve flicker mitigation throughout the entire dynamic range of the image sensor. This is illustrated in Figure 8.

In the first example, a split pixel image sensor is described. In this sensor, flicker mitigation may be achieved by modifying one of the two pixel photodiodes (e.g. by reducing sensitivity of the second photodiode). In this example, the other photodiode is not modified, and behaves as a typical image sensor pixel. This design relies on the assumption that the flickering LED light will be a brighter object in the scene. This assumption is valid in most cases, but will fail if the flickering LED is relatively dim.

In the second example, a second variant of split pixel device is described, in which both photodiodes have flicker mitigation. In this example, flicker is mitigated throughout the dynamic range. However, this would be achieved at the expense of increased sensor complexity and cost.

In the third example, a non-split pixel approach is described. Instead, a charge buffering approach is used to extend the dynamic range of the pixel. However, it is not currently possible to extend the dynamic range of a pixel to 120dB, so a second exposure is required to achieve 120dB, at the cost of intrinsic sensor flicker mitigation.

In the fourth embodiment, a combination of split pixel and chopped exposure technique is described. In chopped exposure pixels, rather than having a single continuous exposure time, multiple very short pixel readouts are performed, and the exposure period is extended. When used in combination with split pixel techniques, both flicker mitigation and high dynamic range can be achieved.

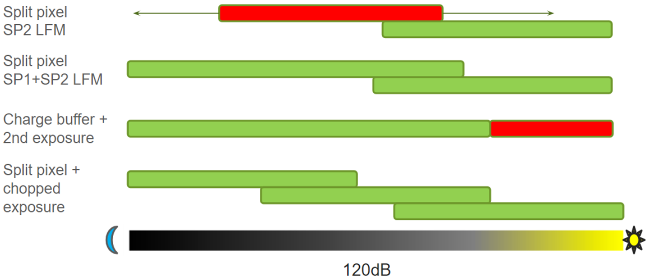

Figure 8. Examples of HDR and flicker mitigation sensor approaches. SP = split pixel photodiode, LFM = LED flicker mitigation. Green indicates flicker mitigation is present, red indicates flicker mitigation is not present.

Ultimately, all approaches described in Figure 8 achieve dynamic range extensions and flicker mitigation, but not necessarily at the same time. This is a crucial consideration for both LED flicker test design and also for the application.

Flicker mitigation via matched exposure time

A key problem for LED flicker mitigation is the fact that there is no standardization of frequency, phase or duty cycle used in automotive application. The only available standard is EN12966:2014 [5], which defines a minimum frequency which must be used (90Hz), to avoid the appearance of flicker to the human eye. In other words, the only requirement for LED headlamps is that they must not flicker to a human observer. Once this requirement is met, any frequency, duty cycle or phase combination is permissible.

This rules out a key potential mitigation strategy for LED flicker. Consider the use case of AC frequency banding mitigation, for example. Banding due to 50/60Hz mains power supply is a very well-known phenomenon, particularly in automotive applications. Briefly, light sources driven by the mains power supply will appear to flicker when imaged by a camera. This is because the AC current powering the lights modulates with a frequency of 50Hz or 60Hz, depending on the geographical region. To prevent banding effects in the image from mains power supply modulation, the solution is to simply ensure that the exposure time of the camera system is an integer multiple of the frequency of the power supply frequency. As the frequencies involved are known, it is a trivial task to define the exposure times required to prevent banding.

However, this solution is not feasible for LED flicker. This is because there is no standard for LED frequencies. As a result, there LED frequency is not known a priori It is therefore not possible to configure the exposure control algorithm in advance with exposure times which match the frequency of the LEDs. In principle, it is possible for advanced image processing algorithms to detect modulation in the image, and compensate for it by modifying the camera's exposure time. However, this will only be effective if there is just one frequency being used in a given scene. As there are no standards for LED frequencies, it is possible, and indeed likely, that more than one frequency, phase and duty cycle of LED light will be in the Field of View (FoV) of the camera, and it is not practical to compensate for multiple frequencies in the FoV at the same time. The most practical solution is therefore to ensure that the exposure time of the camera is sufficiently long to ensure that at least one pulse of the LED being imaged is captured. In this way, it is possible to ensure that the LED does not flicker on/off. This mitigates the appearance of LED flicker, but does not resolve it completely.

Measuring LED Flicker

When the IEEE P2020 Automotive Image Quality working group was established, a key consideration was the definition of KPIs and standard test methodologies for assessing LED flicker. Initial approaches and metrics for defining LED flicker are described previously [1]. The final metrics and test methodologies will be defined in the P2020 standard. The following are key considerations which will be included in the test methodology, when released in the standard.

1. Both cases where the LED is in the FoV, or where the LED is illuminating the scene should be considered
2. Flicker and flicker mitigation should be tested throughout the entire dynamic range of the device under test
3. Steps need to be taken to ensure the camera's auto exposure algorithm (if present) do not interfere with measurements
4. Care needs to be taken when selecting the LED frequency to test. Depending on the frequency of the LED light and the frame rate of the camera under test, it is possible that the LED light may appear constantly on or constantly off. This can cause a misleading measurement
5. Both human viewing and machine vision applications need to be considered in the test protocol

All of the above points will be taken into account in the P2020 standard.

Conclusion

LED flicker is an increasingly widespread concern for automotive imaging. Depending on the scenario, LED flicker can cause a number of issues, ranging from driver annoyance/distraction to negatively affecting machine vision algorithm performance. Understanding both the use cases and mitigation strategies is key to defining standards and metrics for flicker mitigation evaluation. IEEE P2020 are actively working on defining these standards.

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Author Biography

Brian Deegan received a PhD in Biomedical Engineering from the National University of Ireland, Galway in 2011. Since 2011 he has worked in Valeo Vision Systems as a Vision Research Engineer focusing on Image Quality. His main research focus is on high dynamic range imaging, surround view harmonization algorithms, LED flicker, and the relationship between image quality and machine vision.

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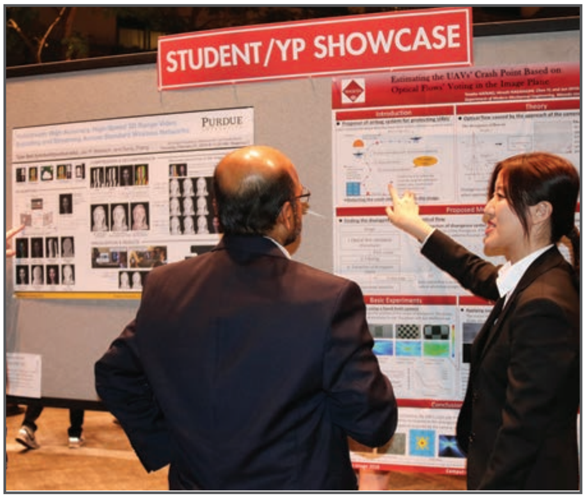

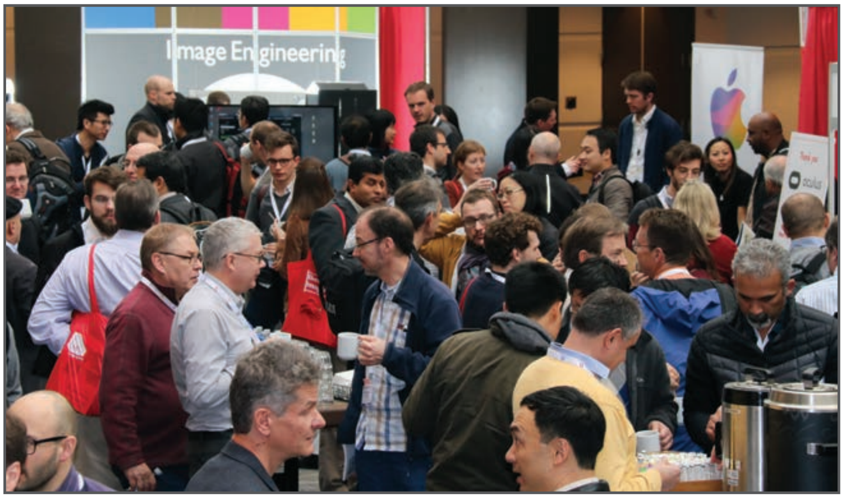

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