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Tutorial

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Active gated imaging in driver assistance system

Abstract: In this paper, we shall present the active gated imaging system (AGIS) in relation to the automotive field. AGIS is based on a fast-gated camera and pulsed illuminator, synchronized in the time domain to record images of a certain range of interest. A dedicated gated CMOS imager sensor and near infra-red (NIR) pulsed laser illuminator, is presented in this paper to provide active gated technology. In recent years, we have developed these key components and learned the system parameters, which are most beneficial to nighttime (in all weather conditions) driving in terms of field of view, illumination profile, resolution, and processing power. We shall present our approach of a camera-based advanced driver assistance systems (ADAS) named BrightEye™, which makes use of the AGIS technology in the automotive field.

Keywords: active gated imaging system (AGIS); active safety; advanced driver assistance systems (ADAS); gated CMOS imager sensor (GCMOS); laser.

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1 Introduction

In recent years, much effort has been devoted to developing advanced driver assistance systems (ADAS) for day and night lighting conditions [1–3]. The purpose of these safety aid systems is typically, early warning – to alert the driver of hazards and accident mitigation – where a collision with an obstacle (e.g., vehicle, pedestrian, animal, etc.) might occur.

Various European ADAS programs have been funded in recent years with the objective of introducing new detection technologies, low-cost products, and high performance capabilities, based on lasers [4, 5].

Autonomous vehicles are also a growing domain, which is targeted for the next decade. These trends have brought the National Highway Traffic Safety Administration (NHTSA) and the European New Car Assessment Programme (Euro NCAP) to introduce ‘active safety’ in new vehicles, as a significant contribution to the overall star rating. Euro NCAP has defined vehicle scoring (vehicle star rating) for car-to-car (rear stationary, rear moving, rear braking) during daytime and is in the process of defining it for car-to-car and car-to-pedestrian during daytime and at nighttime, partially based on ActiveTest European program findings [6]. Various vehicle manufacturers are already introducing driver assistance systems [7].

Lasers are being introduced in various products in the automotive market such as; scanning light detection and ranging (LIDAR), time-of-flight (TOF) camera/illuminator (e.g., internally in the passenger compartments and externally to the vehicle) and even as headlights (visible and NIR).

BrightEye™, a patented active gated day and night vision safety ADAS, certified EAR 99, utilizes a repetitive pulsed NIR extended laser source in the vehicle headlights coupled to a gated high-resolution image sensor to provide an active gated image.

2 Overview of forward-facing driver assistance systems

2.1 Optical sensing technologies

Optical sensing technologies in the automotive field / industry consist mainly of the following technologies:

- *CMOS imager sensor (CIS)*: a mono camera configuration operating in the visible/NIR spectrum providing a 2D image. A stereo camera configuration provides 3D information based on triangulation [7].
- *Avalanche pin diode (APD)*: a mono sensing configuration operating in the NIR spectrum coupled to a laser scanner providing a 3D point cloud low resolution image based on pulsed TOF (e.g., IBEO Automotive Systems [8], SICK [9]).
- *Time-of-flight (phase modulation):* a mono sensing configuration operating in the NIR spectrum coupled to a LED/laser source providing a 3D low-resolution image based on phase delay TOF (e.g., PMD Technologies [10]).

– *Solid state image sensors*: a mono camera configuration operating in the long wave infra-red (LWIR) or short wave infra-red (SWIR) spectrum providing a 2D image (e.g., FLIR [11]).
– *Gated CMOS imager sensor (GCMOS)*: a mono camera configuration operating in the visible/NIR spectrum providing a 2D image and 3D raw information. A stereo camera configuration provides 3D information based on triangulation. (e.g., BrightWay Vision [12]).

2.2 Night vision technologies

AGIS utilizes a repetitive pulsed NIR beam above 0.8 μm to illuminate the scene and then detects the reflected pulsed light with a synchronized gated image sensor.

There are two additional types of night vision technologies on the market: long wave infra-red (LWIR) and NIR systems. LWIR systems are passive, detecting the thermal radiation at wavelengths in the interval 8–14 μm. NIR systems use a continuous light source with a wavelength of above 0.8 μm, to illuminate the scene and continuously detect the reflected light with a high dynamic range (HDR) image sensor. Widespread use of both technologies is currently limited by the systems performance and cost [13]. Figure 1 illustrates the night vision technologies in the automotive field.

A combination of technologies is also available such as active NIR, passive LWIR, Radar, etc.

Based on the night vision image feed, additional functionalities are available such as; pedestrian detection, spotlighting, and animal detection.

3 Active gated imaging system description

Active gated-imaging technology incorporates a range gating technology, based on multiple 'time-of-flight' events,

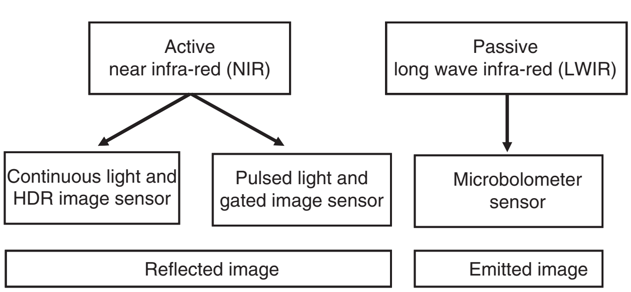

Figure 1 Night vision technologies in the automotive field.

per single readout frame in the sensor. Unlike other night vision technologies, range gating does not require ambient light sources and do not require radiation signature emission (i.e., temperature difference) used by thermal imaging.

Active gating technology combines two key components: a pulsed light source (i.e., laser, LED) beam and a specially designed gated sensor that exposes and opaques light at high speeds (in the order of 0.01–2 μs). Each reflected light source pulse is accumulated in the gated sensor based on a specific 'time-of-flight' event. Once a desired signal (corresponding to a desired depth-of-field) is accumulated in the sensor, the image is read out; thus, providing high signal-to-noise ratio (SNR) with relatively low peak power illumination.

AGIS for automotive use was first described in a previous work, where the gated camera was based on an image intensifier attached to a CCD imager [14, 15]. The system only provided video to the driver, in various nighttime weather conditions.

Sensing, and lighting technology advances and image processing progress recently has taken the BrightEye™ ADAS, based on active gated imaging for the automotive field, to an advanced stage where a superb image and automatic obstacle detection is provided [16].

BrightEye™ has been certified EAR 99 [17] by the U.S. Commodity Jurisdiction (i.e., does not require a license to be exported or re-exported).

3.1 Active gated imaging prototype system

Figure 2 depicts a BrightEye™ prototype block diagram comprising two main modules; a camera unit and an illuminator unit (i.e., light source). The block diagram describes a day/night and close/far range ADAS solution, exploiting a common hardware/processing infrastructure.

3.2 Active gated imaging modules

The camera unit consists of a dedicated gated image sensor; gated CMOS imager sensor ('GCMOS') fabricated in 0.18 μm CMOS technology. GCMOS has three operating modes: single exposure, repetitive exposure mode, and standard mode. GCMOS provides:

1. For single/repetitive exposure mode: high efficiency per exposure in a single image frame (which is read out of the imager).
2. High opaqueness during non-exposure.
3. High antiblooming ratio (above 5000) between pixels. Required to prevent halo from reflective objects in the

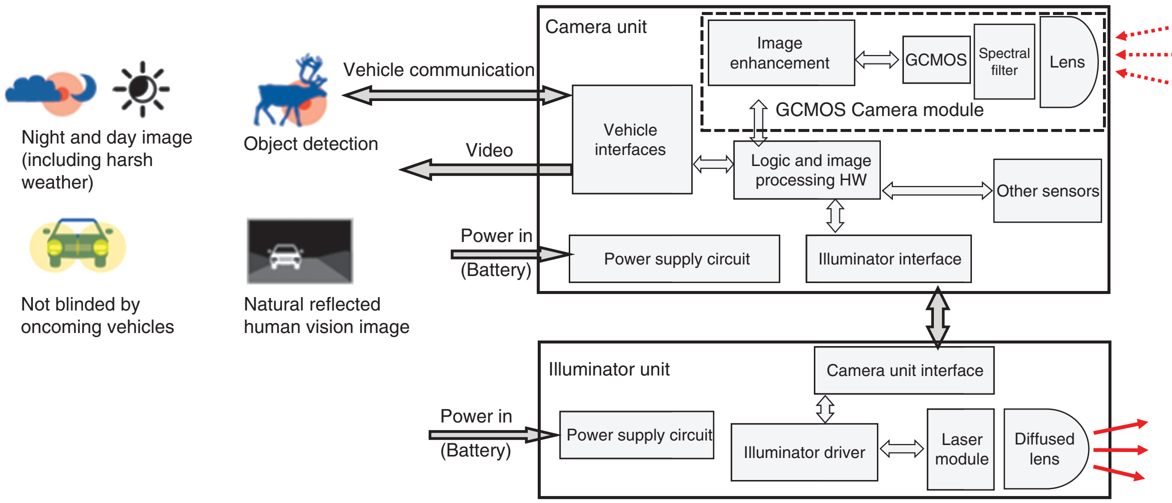

Figure 2 BrightEye™ prototype block diagram.

illuminated camera field-of-view, such as traffic signs or retro-reflectors [18]. Furthermore, this high ratio contributes to cope with similar systems heading toward each other.

4. High sensitivity in the NIR, above 50% (quantum efficiency).

The GCMOS pixel array exposure is synchronized to a single illumination pulse in single-mode operation. In repetitive exposure mode, each GCMOS pixel array exposure is synchronized to each illumination pulse in a single image frame. In contrast with the former operation modes in standard mode, GCMOS pixel array exposure is not synchronized to the system illumination scheme.

An optical design provides the required field-of-view by an objective lens with a spectral filter. A real-time processor handles system control, image enhancement, and image processing. The image computer/machine vision provides the ADAS features. In addition, the system is connected to the vehicle communication bus to provide ADAS features and provides AGIS video feed. Camera unit may be integrated into the existing vehicle sensor cluster, which is usually located in front of the rear-view mirror and behind the windshield, at the top of the windshield and close to the centerline of the vehicle (behind the cleaned area of the wipers).

The illuminator unit consists of a laser module at the NIR, preferably a surface emitting laser, due to the following considerations:

1. Lower wavelength shift as to temperature variance vs. LED.
2. High uniformity of beam profile.
3. Convenient for rescaling (i.e., based on the number of emitters).
4. Compliance to automotive requirements (i.e., environmental, reliability etc.).

Laser is preferred over other means of illumination such as LED, flash lamp, etc. due to its narrow spectral width (of the order of several nm), high peak power (on the order of a few hundred watts), and high efficiency (above 40%). The laser module is driven by a controller providing synchronization of each laser pulse to each camera exposure (gate). A diffused optical design provides the required illumination angular distribution. The illuminator unit may be integrated into an existing vehicle headlight or as a separate headlight.

BrightEye™ illumination energy distribution is provided by a simple Eq. (1) [19].

$$E_{SP}(R)=\frac{P_L\tau_L t_L}{\left[A_H+2R\tan\left(\frac{\theta_H}{2}\right)\right]\left[A_V+2R\tan\left(\frac{\theta_V}{2}\right)\right]} \quad (1)$$

where, P_L is the laser peak power, τ_L is the optical transmission, t_L is the effective pulse duration, A_H/A_V are the beam dimensions on both axis, θ_H/θ_V are the beam divergence on both axis, and R is the distance. Illumination loss due to atmospheric absorption is negligible.

BrightEye™ prototype parameters are noted in Table 1.

An active gated imagery at nighttime is presented in Figure 3. The image was taken with a low-resolution GCMOS test chip (360 by 180 pixels) synchronized to an illuminator unit.

Table 1 BrightEye™ active gated imaging main parameters.

Camera unit	
Gated image sensor type	Gated CMOS imager sensor ('GCMOS')
Operating modes	– Single exposure mode – Repetitive exposure mode – Standard mode
Gated image sensor single exposure duration	Typically 0.5–2 μs
Gated image sensor resolution	1280×960 pixels
Frame rate	120FPS (@1280×480 pixels)
Illuminator unit	
Laser type	Laser diode
Operating method	Repetitive pulses with a very low overall duty cycle
Wavelength	Typically in the region of 800–860 nm
Single pulse duration	Typically 0.5–2 μs (FWHM)
Average optical power	<5 W
Field-of-illumination	Extended diffused source with large divergence angles

Figure 3 BrightEye™ raw imagery at night. Three dummy objects are noticeable (200 m, 150 m, and 100 m), a vehicle with low-beam headlamps at 75 m and a traffic sign (i.e., retro-reflector sign) is located 50 m from the AGIS.

Figure 4 BrightEye™ raw imagery during daytime. Three people are noticeable at about 70 m.

An active gated imagery during daytime is presented in Figure 4. The image was taken with a low-resolution GCMOS test chip (360 by 180 pixels) without a pulsed NIR illuminator unit.

4 Active gated imaging challenges

BrightEye™ key components (GCMOS and pulsed laser module) were developed specially for active gated imaging, and emphasis was made in order to fulfill automotive imaging and sensing requirements. These requirements (cost/functionality, technical) are met with BrightEye™ system, starting with the key components design and further on with additional capabilities, such as computer vision features.

A short example can shed some light on the complexity of the BrightEye™ design. The gating mechanism in the GCMOS (installed behind the windshield) has to be sensitive enough to detect a single exposure event of a diffusive object (e.g., pedestrian) at 200 m (e.g., required for enhancing computer vision performance, high velocities), where the laser module optical power is limited due to cost/safety constraints.

In addition, in repetitive exposure mode, the multiple events should be efficient (or not add too much gating noise), synchronized in the order of ns per exposure and provide a sufficient SNR active gated image at nighttime or during daytime.

Another example is that the BrightEye™ GCMOS design has to cope with interscene high dynamic ranges (e.g., an opposite vehicle with high-beam headlamps facing BrightEye™) and provides a good image.

5 AGIS-integrated ADAS solutions

BrightEye™ 'open architecture' can be integrated in various ADAS solutions, to provide versatile imaging capabilities and outstanding system functionalities.

5.1 Mono vision configuration

BrightEye™ mono vision configuration may include:

1. Narrow FOV (e.g., 24° horizontal by 8° vertical) to provide a long-range nighttime imaging of above 200 m.
2. Wide FOV (e.g., 48° horizontal) to provide a midrange nighttime imaging of above 70 m. This option is highly applicable for approaching low-light level Euro-NCAP requirements.

5.2 Stereo vision configuration

BrightEye™ stereo vision configuration includes a wide FOV to provide a midrange nighttime imaging enhancement to existing stereo vision standard, which is currently limited to vehicle headlamp illumination pattern.

5.3 Multi-spectral vision configuration

BrightEye™ may be integrated in a multi-spectral vision configuration that includes a near infra-red (NIR) active gated imaging and a LWIR sensing technology. In this configuration, a fused spectral detection may be beneficial for automatic computer vision alerts.

5.4 Multi-sensing configuration

BrightEye™ may be integrated in a multispectral vision configuration that includes a NIR active gated imaging and other types of sensing technologies such as LIDAR, radar, acoustic, etc. In this configuration, a fused detection may be beneficial for automatic computer vision alerts.

5.5 'Open spectral' configuration

GCMOS imager sensor can be hosted in a camera-based ADAS, replacing a standard CMOS imager sensor (CIS). This unique GCMOS can provide improved day and night performance as to standard CIS and provide a solution to flickering (i.e., pulse-width-modulation operation) LED lights (e.g., break light, traffic signs, etc.).

Figure 5 illustrates capturing a scene during daytime consisting of flickering LED signs. The images were taken sequentially with a standard CIS having a limited exposure time due to automatic gain control mechanism. Each frame has different color/intensity/partial LED sign information.

Figure 5 Four frames of flickering LEDs during daytime with a standard CIS.

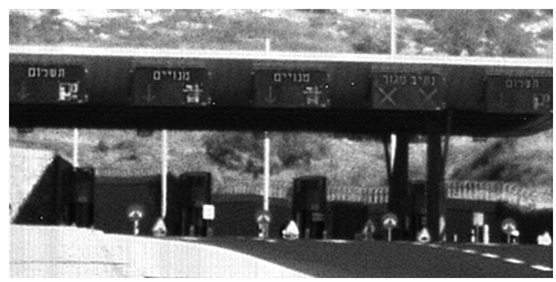

Figure 6 BrightEye™ raw imagery of flickering LEDs during daytime.

Figure 6 illustrates capturing the same scene via a low-resolution GCMOS test chip (360 by 180 pixels), without a pulsed NIR illuminator unit, with the same lighting conditions as Figure 5. The repetitive exposure scheme in a single readout frame provides a single image with a full LED sign information.

In addition, this configuration provides a linear high dynamic range capabilities to cope with interscene dynamic range (e.g., sun light). Spectral filters can be implemented in the pixel array level as a mosaic filter array or any other pattern.

6 ADAS functions by active gated imaging system

Currently, BrightEye™ configurations as illustrated in Figure 2, consist of a spectral filter transmitting in the NIR. Despite the lack of color information, BrightEye™ image quality enables multiple ADAS capabilities/functions.

6.1 All-weather night image

At nighttime, BrightEye™ active gated technology is providing two main advantages, as to its image quality vs. a continuous wave active NIR image (i.e., continuous NIR light and HDR image sensor):

1. Immunity to backscatter medium (such as dust particles, rain droplets, snowflakes, etc.) in the atmosphere.
2. Unified signal in the entire depth of field.

The governing parameter of an active imaging performance is the modulation contrast, which is defined as ‘Contrast’ in Eq. (2) [14]. Taking into account the air light (for night vision application using a spectral filter, there is very little or no air light), which is in this context, light from ambient light sources that are scattered into the system’s field of view (FOV) and backscatter, which add to the target (object) and background.

$$\text{Contrast}=\frac{I_{\text{Target}}^{\text{Total}}-I_{\text{Background}}^{\text{Total}}}{I_{\text{Target}}^{\text{Total}}+I_{\text{Background}}^{\text{Total}}}\cong\frac{I_{\text{Target}}-I_{\text{Background}}}{I_{\text{Target}}+I_{\text{Background}}+2I_{\text{Backscatter}}} \qquad (2)$$

The radiance of the atmosphere within the FOV is calculated by summing the backscatter contributions of all illuminated particles on the path between the image sensor and the scene. The backscatter ratio between a continuous wave active NIR to an active gated NIR (having the same FOV, F number, light source intensity, light source beam divergence and backscatter gain) is given in Eq. (3) [14].

$$\xi(R_{\max},R_{\min1},R_{\min2},\gamma)=\frac{\int_{2\gamma R_{\min1}}^{2\gamma R_{\max}}\frac{e^{-X}}{X^2}dX}{\int_{2\gamma R_{\min2}}^{2\gamma R_{\max}}\frac{e^{-X}}{X^2}dX} \qquad (3)$$

X is the integration variable, and R_{min}/R_{max} are the ranges from the imaging system (including the illuminator) to the nearest/longest illuminated scene.

Figure 7 illustrates this backscatter ratio for an atmospheric attenuation coefficient of γ=0.2 km^{-1} (i.e., clear to light haze), γ=2 km^{-1} (i.e., light fog), R_{max}=300 m, R_{min1}=1 m (i.e., illuminator/sensor are typically located in different places in the vehicle), and the R_{min} values are different for each type of operation method (e.g., continuous wave or gated mode).

This result explains the higher modulation contrast of an active gated imaging vs. a continuous wave active imaging system in standard and harsh weather conditions.

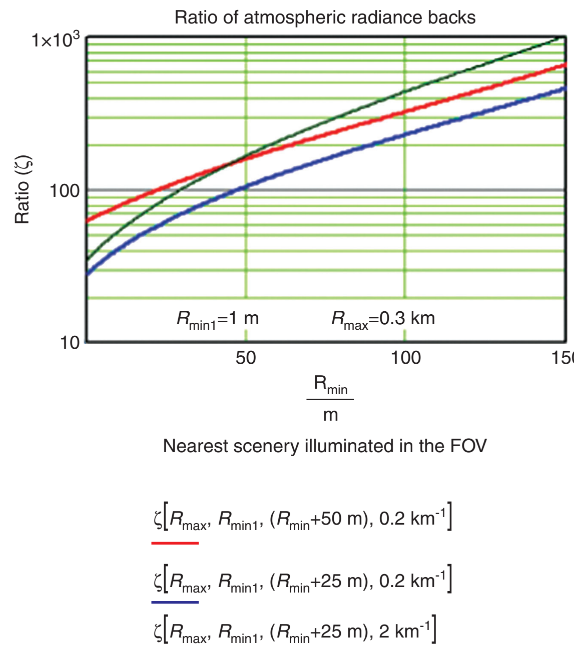

Figure 7 Backscatter ratio for active imaging in continuous wave vs. gated mode.

Figure 8 demonstrates the immunity of active gated imaging to backscatter medium during snow (heavy snowfall conditions, visibility is restricted below 0.5 km) at nighttime. A pedestrian is easily noticeable at near and far distances. The images were taken with the following system configuration: repetitive exposure mode, single exposure duration of 1 μs, single pulse duration of 1 μs, and average optical power of 3 W.

Unified signal in the entire depth of field is another advantage this technology offers. The gating method

Figure 8 BrightEye™ imagery of a pedestrian between 50 m to 120 m during snow at night.

enables the GCMOS to accumulate a unified and controlled signal independently to the viewed range. This feature solves ‘inverse R square’ law (i.e., close objects are very intense in reflected signal vs. long distance objects, which have a low reflected signal). The result is providing a night-image similar to day image, regarding the intensity distribution, as can be seen in Figure 9. The image was taken with the same system configuration as in Figure 8.

6.2 Obstacle detection

An additional capability of active gated imaging vs. other camera-based driver assistance systems, is the ability to ‘remove’ or ‘exclude’ background at a specific range (i.e., selective depth of field). The range maybe determined by the speed of the vehicle or any other computer vision weighing consideration. Clutter reduction provides significant reduction in false alarm rate (FAR) while maintaining high probability of detection (POD) for obstacle detection such as pedestrians, animals, or other types of obstacles. These selective depths of field images can be fed to computer vision, viewer, or any other user.

Figure 10 illustrates two different selected depths of field at nighttime. These consecutive images were taken in an urban scenario. The top image is a ‘full’ depth of field image up to 250 m where the bottom image is a ‘partial’ depth of field image up to 70 m. The clutter removal is extensive with this gating method as described in [16]. The selective depth of field is based on different time synchronization between the sensor and illuminator. The image was taken with the same system configuration as in Figure 8.

6.3 Forward collision warning

For forward collision warning (FCW), active gated imaging can provide an additional dimension of information vs. a standard camera-based ADAS. The additional information

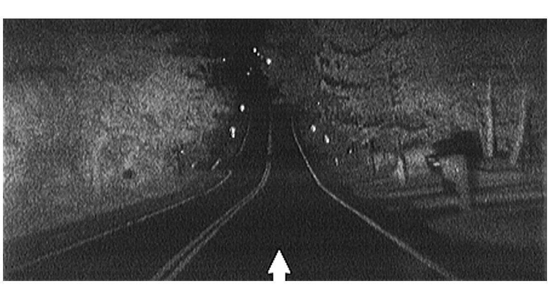

Figure 9 BrightEye™ imagery at night.

Figure 10 BrightEye™ selective depth of field at night.

is the ability to detect vehicle retro-reflectors during daytime, at nighttime, and in harsh weather conditions, while ‘removing’ other types of reflections (i.e., specular or diffusive). Retro-reflectors are mandatory on all road vehicles. Based on this capability, a computer vision algorithm may open a region-of-interest around the relevant detected retro-reflector signal.

Figure 11 illustrates capturing the same scene by a low-resolution GCMOS test chip (360 by 180 pixels) at midday in clear sunny conditions. The upper image is a typical daytime image where the system illumination is contributing only for retro-reflector signal. The lower image is the processed image without the scene background originated due to sun irradiance. The upper image was taken with the following system configuration: repetitive exposure mode, single exposure duration of 0.5 μs, single pulse duration of 0.5 μs and average optical power of 0.5 W.

6.4 Lane departure warning

Lane departure warning (LDW) and lane keeping assist (LKA) are also common functions that are provided by camera-based driver assistance systems. Generally, such systems make use of CIS, which is mounted inside the passenger compartment. A minimal contrast of the lane marking or curb marking is required in order to conduct this computer vision function. In addition, color information of the marking may simplify the detection algorithms.

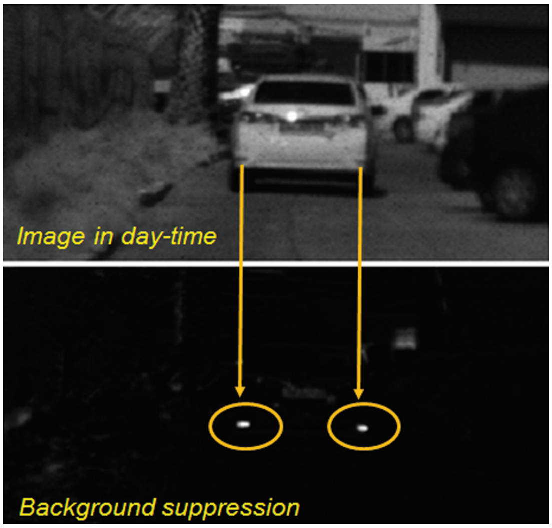

Figure 11 BrightEye™ retro-reflector detection during daytime.

NIR signal is similar to the visible spectrum signal as can be noticed in Figure 12. The images were taken with a system operating in a standard mode.

6.5 Traffic sign detection

Traffic sign detection (TSR) is a common function that is provided by multiple technologies such as navigation systems, vehicle-to-infrastructure (V2I) communications and camera-based driver assistance systems. TSR requires the ability to detect a traffic sign, recognize ('understand') it, and declare the result.

Figure 12 NIR imagery during daytime.

Figure 13 Traffic sign images by BrightEye™ at night.

A camera-based driver assistance system has to provide during day, night, and all-weather conditions a sharp image of the traffic sign for the first stage of detection.

BrightEye™ provides a traffic sign image, which is often based on a retro-reflector, with no halo or blooming around the traffic sign borders at nighttime and with the ability to 'read' the sign contents with image fusion [16]. In addition, color information of the traffic sign may simplify the detection algorithms. Figure 13 demonstrates a BrightEye™ image including traffic signs at nighttime. The image was taken with the same system configuration as in Figure 8.

7 General safety evaluation of active gated imaging system

Laser safety standards such as IEC 60825-1 provide exposure limits, emission limits for safety classification of products, for pulsed exposure, and methods on how to evaluate multiple pulse exposure [20]. International standards did not provide an appropriate approach to ADAS laser products in regard to human accessibility consideration, limiting exposure duration (T_2 as defined in the standard) and product classification (effective measurement distances). A laser safety approach and analysis (based on interlocking to the vehicle's speed) of BrightEye™ was given in a previous work [21].

7.1 AGIS laser safety approach

7.1.1 Fail-safe interlock

BrightEye™ uses a fail-safe interlock. The illuminator unit (laser system) fail-safe interlock is based on the following two conditions:

A. A constant successful system/vehicle communication bus feed, such as CAN communication.
B. The vehicle speed is above a constant threshold, and a processed image validates the vehicle motion.

7.1.2 Human access

The laser system is mounted on a moving platform (vehicle), which does not allow humans to constantly view the laser emission, for a long period of time. Any human located in front of the mounted laser system would be exposed to a higher risk of getting run over by the moving platform (vehicle), than being exposed to laser emission values exceeding laser standard conditions.

Additional aspects are also taken into account such as geometrical considerations of illuminator installation on the vehicle, limiting exposure duration, and collecting optics requirements.

7.1.3 Single fault condition

BrightEye™ accessible emission does not exceed the emission limit, even for reasonably foreseeable single fault conditions. BrightEye™ system has the following reliable automatic hardware and software protections:

A. Each laser pulse is triggered by the camera unit (the camera unit is the 'master', while the laser illuminator unit is the 'slave').
B. The camera unit software does not enable to enter or trigger laser pulse FWHM duration above a certain value.
C. The camera unit software does not enable to enter or trigger laser pulses above a certain threshold.
D. In the laser illuminator unit, an 'AND' gate is implemented for each triggered pulse. The 'AND' gate is implemented in hardware, and the maximal threshold of the pulse FWHM duration is up to a certain duration.

8 Conclusion

BrightEye™ is bringing state of the art cost-effective CMOS imaging and laser illumination technologies coupled with computer vision capabilities.

Active gated imaging seems to be the most promising and suitable technology for camera-based ADAS in automotive for existing standards and future autonomous capabilities in vehicles during day, night, and harsh weather conditions.

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