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TECHNICAL NOTE

AUTOMOTIVE INTERIOR MONITORING SYSTEMS: A REVIEW OF SELECTED TECHNICAL SOLUTIONS FOR THE RECOGNITION OF FATIGUE SYMPTOMS IN MOTOR VEHICLE DRIVERS

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Abstract: Road traffic accidents are one of the leading causes of health loss, disability, and premature death for thousands of people worldwide. There are numerous factors that increase the risk of road accidents, one of which is driver fatigue. Therefore, the aim of this study is to review selected technical solutions available on the market that are used, among other things, to detect signs of driver fatigue and, consequently, to enhance driving safety. The selected vehicle interior monitoring systems are characterized in terms of their design, operating principles, and functionality.

Keywords: Road Traffic Safety, Automotive Interior Monitoring Systems (AIMS), Driver Monitoring Systems (DMS), Occupant Monitoring Systems (OMS)

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INTRODUCTION

Road traffic accidents constitute a significant issue and a major public health challenge, as they are recognized as one of the leading causes of health loss, disability, and premature death for thousands of people worldwide. According to the World Health Organization (WHO) data from December 2023, approximately 1.19 million people die globally each year as a result of road accidents [35]. Factors increasing the risk of road accidents include, among others, driver fatigue and the distraction that often results from it. It is estimated that driver fatigue alone may be responsible for 15–30% of all road accidents [25,34]. To address social needs and expectations, automotive industry specialists, in collaboration with researchers from various fields, are developing innovative technical solutions aimed at enhancing driving safety. Among these solutions are Automotive Interior Monitoring Systems (AIMS), which monitor the vehicle cabin, including the driver and passengers. Since July 2022, Regulation (EU) 2019/2144 of the European Parliament and the Council [22] has been in force in European Union (EU) countries, requiring manufacturers to equip all motor vehicles (including passenger cars, vans, trucks, and buses) with systems that warn about driver drowsiness and decreased attention levels. This requirement applies to newly introduced vehicles subject to type approval.

Given the above, the aim of this study is to review selected driver and vehicle cabin monitoring systems available on the market, used, among other things, to detect signs of driver fatigue and thereby improve road safety. The selected systems are characterized in terms of their design, functionality, and applicability while driving.

Basic functionalities of automotive interior monitoring systems

Vehicle interior monitoring systems include solutions designed to track both the driver and the passengers inside the vehicle. Depending on the manufacturer, Driver Monitoring Systems (DMS) and Occupant Monitoring Systems (OMS) may feature various functionalities, which are characterized below.

Driver Fatigue Detection. The system can detect signs of driver fatigue by monitoring the eyes, mouth, and head position. In real-time, it collects and processes data related to the following parameters: percentage of eye closure time (PERCLOS), eye closure duration (ECD), eye blink frequency (FEC) [6], yawning frequency, as well as head tilt or drooping.

Driver Distraction Detection. The system can identify when the driver is not observing the road by monitoring the driver's gaze direction and head position. It continuously collects and processes

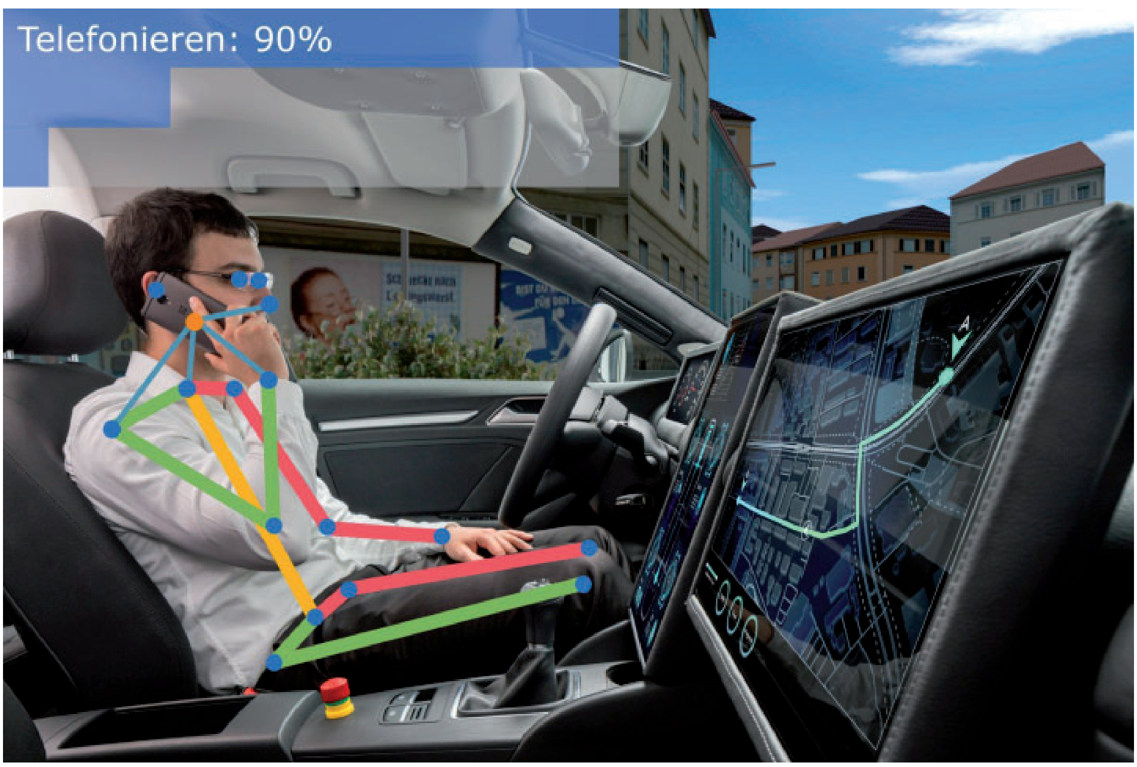

Fig. 1. Driver activity detection using skeletal key point analysis – Fraunhofer IOSB [40]

Table 1. Selected Passenger Car Brands Equipped with DMS Systems.

Passenger cars equipped with the DMS system			
Company	System name	Important features	References
BMW	Attentiveness assistant/ Driver Attention Camera	Evaluates the driver's distraction level; used with Active Cruise Control (ACC). A face--directed camera tracks eye movements to ensure the driver's gaze remains focused on the road.	[3]
FORD	Blue Cruise	Evaluates the driver's distraction level; used with Active Cruise Control (ACC). A face-directed camera tracks eye gaze and head position to ensure the driver remains focused on the road, especially when hands are off the steering wheel. The system alerts the driver if it detects distraction or inattentiveness.	[9]
GM	Super Cruise	Evaluates the driver's distraction level; used with Active Cruise Control (ACC). A face-directed camera tracks eye gaze and head position to ensure the driver's focus is on the road, particularly when their hands are off the steering wheel. The system alerts the driver if it detects an abnormal condition, such as distraction.	[12]
HONDA	Honda Sensing 360+/Driver Emergency Support System	Detects driver loss of consciousness based on eye and head position monitoring. Used for emergency vehicle stop and notifying emergency services.	[14]
MAZDA	i-Activsense Safety Systems/ Driver Monitoring (DM)	Detects driver loss of consciousness based on eye and head position monitoring. Used for emergency vehicle stop and notifying emergency services.	[19]
MERCEDES-BENZ	Attention Assist	Evaluates the driver's distraction and fatigue levels based on eye observation. The system alerts the driver if it detects an abnormal condition, such as distraction and/or signs of fatigue.	[20]
SUBARU	Driver Focus	Evaluates the driver's distraction and fatigue levels based on eye observation. The system alerts the driver if it detects an abnormal condition, such as distraction and/or signs of fatigue.	[21,27]
TOYOTA	T-Mate Driving Assistance/ Driver Monitor Camera (DMC)	Evaluates the driver's distraction and fatigue levels. The system alerts the driver if it detects an abnormal condition, such as distraction and/or signs of fatigue. The data obtained from this system are used to enhance the effectiveness of the Emergency Braking System (EDSS).	[30]

real-time data regarding the vehicle's direction of movement and compares it with the driver's gaze direction and head position [18].

Detection of Legally Prohibited Behavior. The system can detect the driver holding and using a mobile phone while driving. It can also monitor driver behavior by analyzing the position of skeletal key points (Fig. 1). For example, the system can detect hands-off-the-wheel behavior by analyzing the position of the driver's hand key points relative to the steering wheel [40].

Driver Personal Profile Memory. The system can recognize the faces of vehicle operators and store their individual preferences for seat position, steering wheel placement, and side mirror adjustments, creating a personal driver profile. Upon detecting the driver's presence and recognizing their face, the system checks whether the current seat, steering wheel, and mirror settings match the stored preferences. If they do not, the system automatically adjusts them accordingly [18].

Unattended Child Detection. If the system detects an unattended child inside the vehicle [11], it first unlocks the central locking system and then lowers all windows. Additionally, the system can send an emergency alert via GSM to the vehicle owner's phone, notifying them of the situation.

Integration with the eCall System. If the DMS system detects a lack of driver response to a road situation—such as when the driver's head is down and they do not react to the system's alerts—the system can autonomously initiate an emergency vehicle stop and send an alert to emergency services via the eCall system. This solution is designed to significantly reduce emergency response times, in accordance with EU regulations, thereby helping to decrease the number of fatalities on European roads [8].

Seat Belt Detection and Passenger Weight Estimation. If the DMS system detects that passengers are not wearing seat belts, the driver is immediately notified. Additionally, the system can estimate the body weight of passengers. This weight information is utilized by the vehicle's airbag control system to optimize deployment in the event of a collision [10].

Some DMS systems are equipped with cameras that monitor not only the vehicle's interior but also the external road environment. These systems analyze driving behavior, providing warnings for, for example: unintentional lane drifting or lane departure without signaling. Vehicles equipped with such systems can also autonomously adjust steering to correct the driving path without driver intervention.

Table 1 presents selected passenger car brands equipped with DMS systems along with their key functionalities.

It is important to note that during the vehicle manufacturing process, manufacturers utilize various OEM (Original Equipment Manufacturer) components. The same applies to DMS and OMS

Table 2. Selected OEM components of DMS/OMS systems.

OEM DMS/OMS		
Company/ System name	Important features	References
CIPIA/ "Driver Sense"	Using an embedded computer system powered by AI-assisted software, the system monitors head position, blinking frequency, and gaze direction to determine whether the driver's focus is on the road or if they are potentially distracted or drowsy. The analysis of the driver's current state allows for sending warnings and can be transmitted and integrated with the vehicle's automatic safety systems. The system's functionality is not affected by the driver wearing glasses or a mask.	[5]
GENTEX CORPORATION	The system enables the detection of driver distraction, driver drowsiness, and occupancy of seats in the vehicle, including the presence of a child in the vehicle. The manufacturer offers a DMS module that can be installed in a custom location within the vehicle or a module integrated into the internal rearview mirror. The system's functionality is not affected by the driver wearing glasses.	[1,20,23]
MAGNA INTERNATIONAL	The system enables the detection of driver distraction, driver drowsiness, occupancy of seats in the vehicle, including the presence of a child, passenger classification (based on a previously used face recognition system), detection of properly fastened seat belts, and child safety seats. The system may also include a module for detecting ethanol content in the air exhaled by the driver. The manufacturer offers a DMS module that can be installed in a custom location within the vehicle or a module integrated into the internal rearview mirror.	[18]
TOBII/ "Autosence"	The system enables the detection of driver distraction and driver drowsiness. It tracks gaze and head position, including eye openness, based on the proprietary Tobii EyeCore algorithm. The manufacturer offers a DMS module for installation in custom locations, such as on the steering column, A-pillar, dashboard, center cockpit area, or in the internal rearview mirror.	[28,29]
VALEO/ "Interior Cocoon"	Using an integrated computer system supported by AI software, the system enables the detection of driver distraction, driver drowsiness, and the presence of a child in the vehicle.	[32,33]

systems. Table 2 presents selected OEM components of DMS/OMS systems.

An example solution used for detecting, among other things, driver distraction and symptoms of drowsiness, is the DMS module from GENTEX CORPORATION, shown in Fig. 2. At the center of the module is the camera lens (1), with NIR (Near-infrared) LED illuminator units (2) symmetrically arranged on both sides, each equipped with six diodes and two NIR VCSEL (Vertical Cavity Surface Emitting Laser) units (3). This system is designed for installation in the front-central part of the vehicle's roof. Thanks to this positioning, it is capable of monitoring all occupants inside the vehicle.

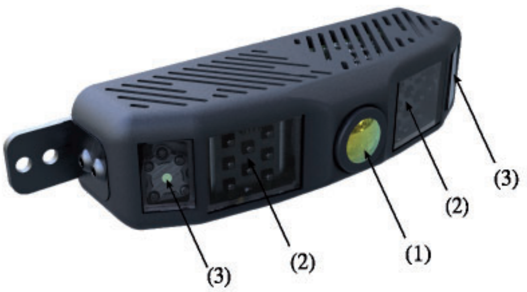

Fig. 2. OEM DMS module, (1) camera lens, (2) LED illuminator, (3) NIR VCSEL – GENTEX CORPORATION [11].

Structure of DMS systems

A typical DMS system, in terms of hardware, consists of: optoelectronic components (NIR light source and camera), microcontrollers responsible for analyzing the recorded image, and microcontrollers for communication with the vehicle's ECU (Electronic Control Units) via the CAN bus (Controller Area Network). Information from the DMS system about a detected event (e.g., signs of drowsiness, distraction, or behavior contrary to traffic regulations) can be communicated to the driver in the following forms: visual (text message, icon on the dashboard, illumination on the steering wheel), auditory (specific sound sequence), and haptic (vibrations in the seat). Under specific circumstances, such as detecting the driver's poor psychophysical state, the data from the DMS sent to the ECU may result in a reduction in vehicle speed or emergency stopping (with hazard lights on).

The DMS system is usually installed in the vehicle cabin in locations that allow for a clear view of the driver's face by the camera. These include: the upper part of the steering column casing, the dashboard, the central part of the cockpit, the rearview mirror, or the front-central part of the vehicle ceiling.

NIR sources in DMS systems

Near-infrared (NIR) refers to the range of electromagnetic radiation with wavelengths from approximately 750 nm to 1400 nm. Currently, in vehicle cabin monitoring solutions, systems that incorporate NIR sources are most commonly used. These types of light sources are chosen for their ability to operate effectively under various lighting conditions that may prevail inside the vehicle cabin. Additionally, NIR sources can be used in darkness, low light, and even under normal daylight conditions. Since the NIR radiation range is invisible to the human eye, NIR sources can be employed for non-invasive measurements, such as monitoring the activity of human eyelids (PERCLOS).

NIR LED

In the construction of DMS systems, NIR LED sources are most commonly used in SMD (surface-

Fig. 3. SMT LEDs: (a) OSLON Black - OSRAM [1], (b) LUXEON IR Compact Line - Lumileds [16,17].

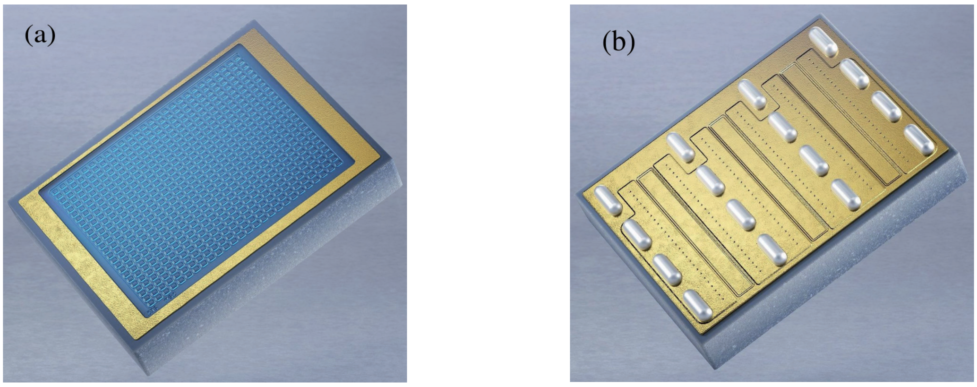

Fig. 4. ViBO module, (a) lens array view, (b) mounting pad view – TRUMPF [31].

mount device) housings, which facilitate SMT (surface-mount technology) assembly on a PCB (printed circuit board). Example SMT LEDs are shown in Fig. 3. LEDs in SMD housings are generally smaller in size than those designed for through-hole mounting.

The size of the spot in NIR LEDs depends on the optics used and the distance to the illuminated object. Depending on the optics used (lenses and collimators), the beam angle typically ranges from 20° to 60° but can reach up to 150°. The greater the distance between the NIR LED and the illuminated object, the larger the spot diameter.

NIR VCSEL

In the latest DMS system designs, NIR VCSELs (Vertical Cavity Surface Emitting Lasers) are used, typically in the form of integrated SMD modules. A single module may contain one or more NIR VCSELs.

The module, embedded in an SMD housing with a group of VCSEL emitters, may also be equipped with a lens array. Fig.4 shows the ViBO module (VCSEL with integrated Backside Optics) in two views: (a) view of the lens array providing diffuse illumination, (b) view of the mounting pads for SMD assembly on a PCB.

To ensure safety for the human body, especially the eyes, applications using NIR VCSELs employ filters to meet the safety requirements specified in Class 1 of the IEC 60825-1:2014 standard [15]. If the filter is damaged or removed, the optical parameters of the NIR VCSEL will correspond to Class 4 for laser devices, meaning they would then be dangerous to human eyes and skin.

Some manufacturers of NIR VCSEL modules solve the safety issue through design. The diffusion optical system is monolithically mounted in a gallium arsenide substrate, making the optical system a permanent, integral part of the ViBO SMD module. This solution eliminates the risk to eye safety, which could arise from damage or disassembly of optical components. For example, this solution is used by TRUMPF in ViBO modules (Fig. 5) [31].

The lenses can have different optical parameters, which, combined with the control of VCSEL emitters (i.e., turning individual emitters on and off), allows the formation of various beam shapes and lighting areas. Fig. 6 shows examples of illumination profiles that can be achieved using ViBO modules: (1) flood, (2) point profile, (3) individually selected area, (4) line-addressed profile.

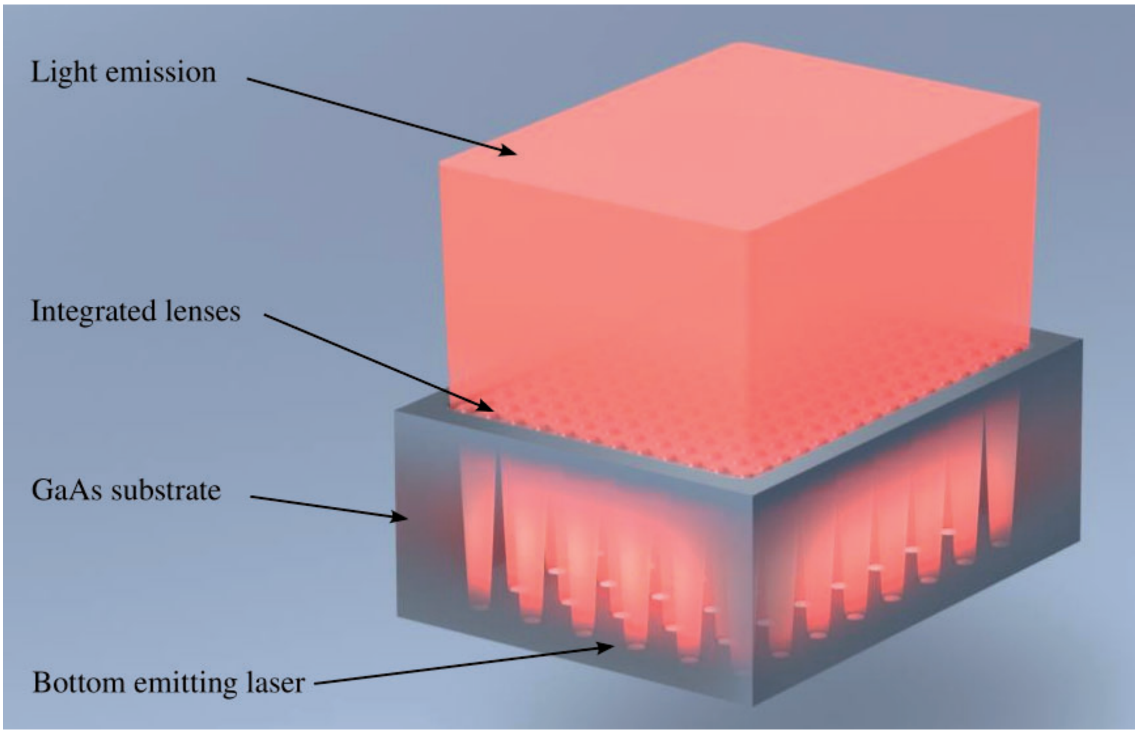

Fig. 5. Construction of the ViBO Module (designed to protect the eyes from harmful effects of NIR VCSEL), TRUMPF [31].

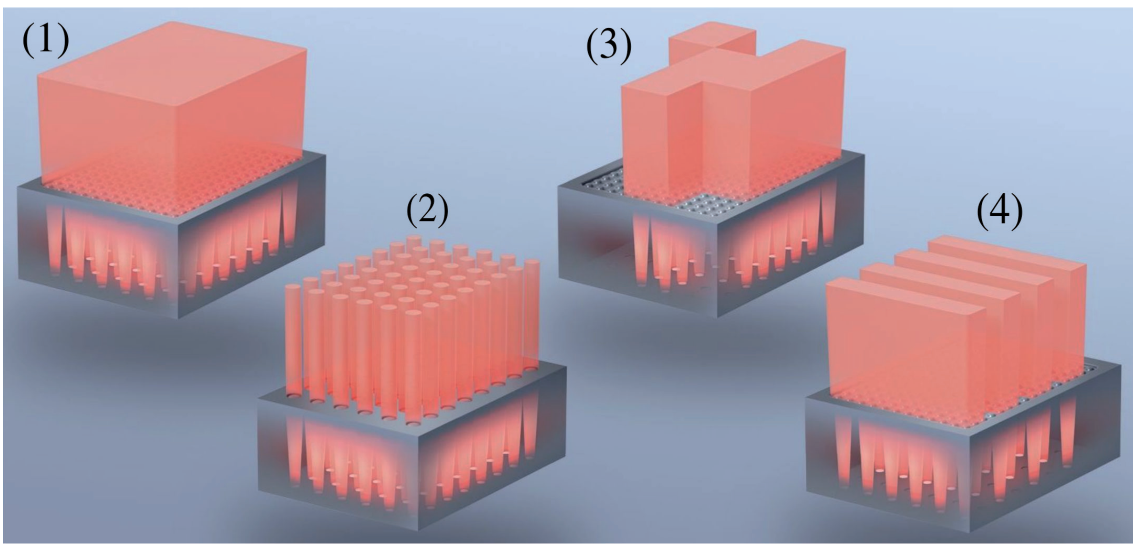

Fig. 6. Formation of different beam shapes in the ViBO module, (1) flood, (2) point profile, (3) individually selected area, (4) line-addressed profile. TRUMPF [31].

The point profile (2) of the beam can be used to recreate an exact 3D model of the driver's face. The individually selected area (3) can be used, for example, to monitor the second row of seats in the vehicle and the space between the seats in the front row.

The size of the light spot emitted by the NIR VCSEL, similar to NIR LEDs, depends on the beam emission angle and the distance to the illuminated object. Compared to NIR LEDs, VCSEL lasers feature a narrower emission angle, typically ranging from 10° to 30°. As a result, when illuminating the same object from the same distance, the light spot generated by the VCSEL is significantly smaller than that produced by the LED.

Table 3 shows the technical parameters of selected VCSEL modules from three different manufacturers that could be used in the construction of DMS.

The VCSEL modules presented in Table 3 have similar technical parameters. The main differentiating parameter between these modules is the beam emission angle in both the horizontal and vertical

Table 3. Technical parameters of selected VCSEL modules.

VCSEL modules			
Manufacturer	AMS OSRAM	WÜRTH ELEKTRONIK	STANLEY
Model	TARA2000-940-W-AUT-SAFE [2]	WL-VCSL [36]	UEN1ZA9-TR [26]
Wavelenght	932 ÷ 940 nm	930 ÷ 950 nm	930 ÷ 950 nm
Spectral width	0.1 ÷ 3 nm	2 nm	1.5 nm
Horizontal FOI (Field of Interest/Illumination)	112º ÷ 120º	85º ÷ 110º	110º
Vertical FOI (Field of Interest/Illumination)	83º ÷ 91º	45º ÷ 60º	85º
Operating ambient temperature	-40ºC ÷ 125ºC	-20ºC ÷ 85ºC	-40ºC ÷ 125ºC
Overall dimensions of the module	4x4x1.2 mm	3x3.5x1.7 mm	3.5x3.5x1.2 mm

Table 4. Comparison of technical parameters of NIR light sources: IR LED and IR VCSEL.

NIR light sources comparison		
	IR LED	IR VCSEL
Beam range	shorter	longer
Beam angle [º]	20º to 150º	5º to 10º
Spot size [mm].	from a few mm	less than 1 mm
3D sensing method	TOF, Stero Vision	Pattern-Based
Safety of the eyes	Fulfilled	Preserved provided the requirements are met Safety Standard 1 of IEC 60825-1
Cost of application	low	major

planes, which affects the size of the area covered by radiation in the vehicle cabin space. An OMS system using a VCSEL module with a wide beam emission angle will require just one such module per vehicle cabin to monitor the driver and passengers. On the other hand, an OMS system using a VCSEL module with a narrower beam emission angle will need at least two such modules.

COMPARISON OF NIR LIGHT SOURCE PARAMETERS

2D and 3D measurement methods using IR LEDs do not require a very precise light pattern, but rather an accurate measurement of the signal return time. The wide, diffuse illumination provided by IR LEDs is perfect for this purpose. IR LEDs are cheaper to manufacture, and applications using them are more economical.

IR VCSEL sources are more expensive to produce than IR LEDs due to the more advanced manufacturing process, but in return, they offer better accuracy in 3D measurements and are therefore preferred in more advanced solutions. Table 4 presents a comparison of the technical parameters of NIR light sources: IR LED and IR VCSEL.

Due to limitations in 3D measurement accuracy (such as: Time-of-Flight, stereo vision), DMS equipped with IR LED lighting are well-suited for detecting driver fatigue based on eye and mouth observation. On the other hand, DMS equipped with IR VCSEL lighting, due to the high accuracy of 3D measurements (Pattern-Based), are not only well-suited for detecting driver fatigue but also for detecting distraction and detecting illegal behaviors.

CAMERAS USED IN DMS SYSTEMS

In DMS applications, cameras with NIR sensors are used. Due to high costs, CMOS (Complementary Metal-Oxide-Semiconductor) technology sensors are more commonly used, while InGaAs (Indium Gallium Arsenide) technology sensors are used less frequently. Depending on the manufacturer, different communication interfaces with varying data transmission speeds are used in the cameras. The sensors also have various image resolution capabilities and recording speeds. In all cameras, it is possible to increase the recording speed at the expense of reducing the ROI (Region of Interest). This solution can be applied when it is not necessary to process the entire scene captured by the camera, but only a selected portion of it. Table 5 presents examples of cameras available on the market with NIR sensors.

WORKING PRINCIPLE OF DMS SYSTEMS USING NIR LED

In order to properly recognize signs of fatigue and driver distraction during driving, DMS systems need to gather information about the position of the head and specific points on the surface of the head within the vehicle cabin. In systems based on NIR LED technology, such information is obtained using methods based on stereovision and the Time-of-Flight (ToF) method [7].

Table 5. Selected models of cameras with NIR sensors.

NIR CAMERAS					
Camera manufacturer	XIMEA	SIMTRUM	XIMEA	XIMEA	CANON
Model	MQ013RG-ON-S7	STNIRE2100KPA	MX022RG-CM	MX042RG-CM	CX-A0500CIR-105
Sensor	CMOS Near Infrared enhanced	CMOS Near Infrared enhanced	CMOS Near Infrared enhanced	CMOS Near Infrared enhanced	CMOS RGB Near Infrared
Sensor manufacturer/ sensor model	ONSEMI/ PYTHON 1300 NOIP1FN1300A–QDI	SONY/ IMX462LQR	AMS OSRAM/ CMOSIS CMV2000 3E12M1PP	AMS OSRAM/ CMOSIS CMV4000 3E12M1PP	CANON/ CMOS LI5020SAI
Resolution [pixels]	MP 1.3 1280×1024 pixels	MP 2.1 1920x1080 pixels	MP 2.2 2048×1088 pixels	MP 4.2 2048×2048 pixels	MP 5 2592x2056 pixels
Recording speed [fps]	210 fps for 1.3 MP resolution +1000 fps for ROI 640x400	120 fps for 2.1 MP resolution	337 fps for 2.2 MP resolution	180 fps for 4.2 MP resolution	102 fps for 5 MP resolution
Communication interface	USB 3.1 Gen1	USB 3.1 Gen1	PCI Express Gen2 x2	PCI Express Gen2 x2	CoaXPress CXP6
References	[37]	[24]	[38]	[39]	[4]

Figure 7 illustrates the method using the ToF measurement in DMS systems. The ToF method involves measuring the time it takes for light emitted by an LED to reach an object, reflect off of it, and return to the detector. This time is proportional to the distance the light pulse has traveled.

The stereovision method is based on the principles of stereoscopy, where distance and depth are calculated based on the differences in the view of the same object from two different viewpoints. The LED acts as a light source, and two detectors (cameras) are placed at a certain distance from each other. The working principle of this solution mirrors the natural mechanism by which human eyes perceive depth and distance. Figure 8 illustrates a method based on stereovision in DMS systems using NIR LEDs.

WORKING PRINCIPLE OF DMS SYSTEMS USING VCSEL

VCSEL emits a pattern of points (a grid) onto the surface of the driver's face. The point pattern is projected in order to measure the distance from various points on the surface of the face.

When the light from the VCSEL illuminator reflects off the face, the point pattern gets distorted depending on the shape and contours of the face. This distortion of the pattern provides information about the topography of the surface. A camera equipped with an NIR sensor records the reflected point pattern. The received data is analyzed by algorithms, which, based on the distortions in the point pattern, calculate the distances from various characteristic points on the face. This allows the creation of a three-dimensional model (also known as a depth map) of the driver's face. Figure 9 presents a DMS system using a single illuminator VCSEL system with Diffractive Optical Elements (DOE). In this application, DOE serves to split the VCSEL beam and create the point pattern projected onto the face. In newer DMS applications with VCSEL, ViBO is used, which enables more accurate measurements of point pattern distortions. The precise three-dimensional model of the driver's

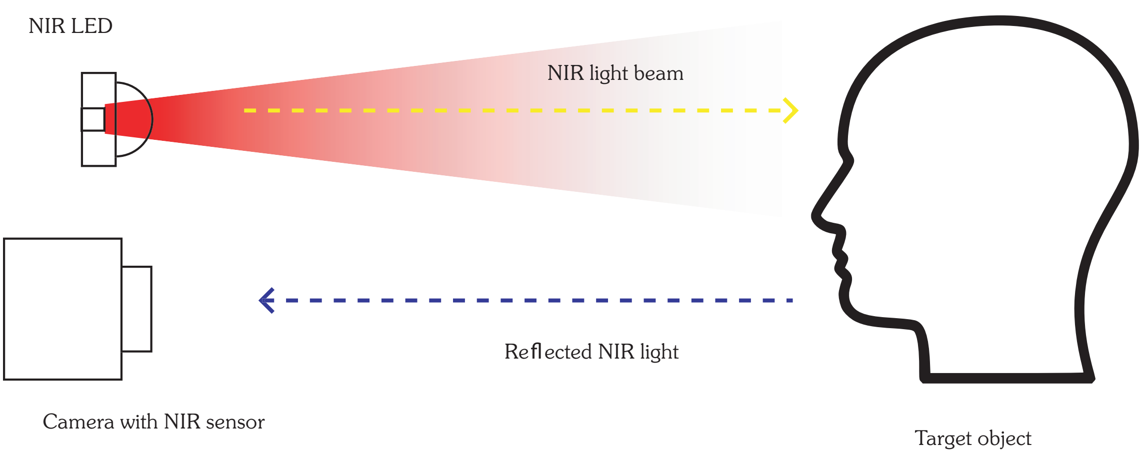

Fig. 7. Time-of-Flight (ToF) method in DMS systems using NIR LED (original design).

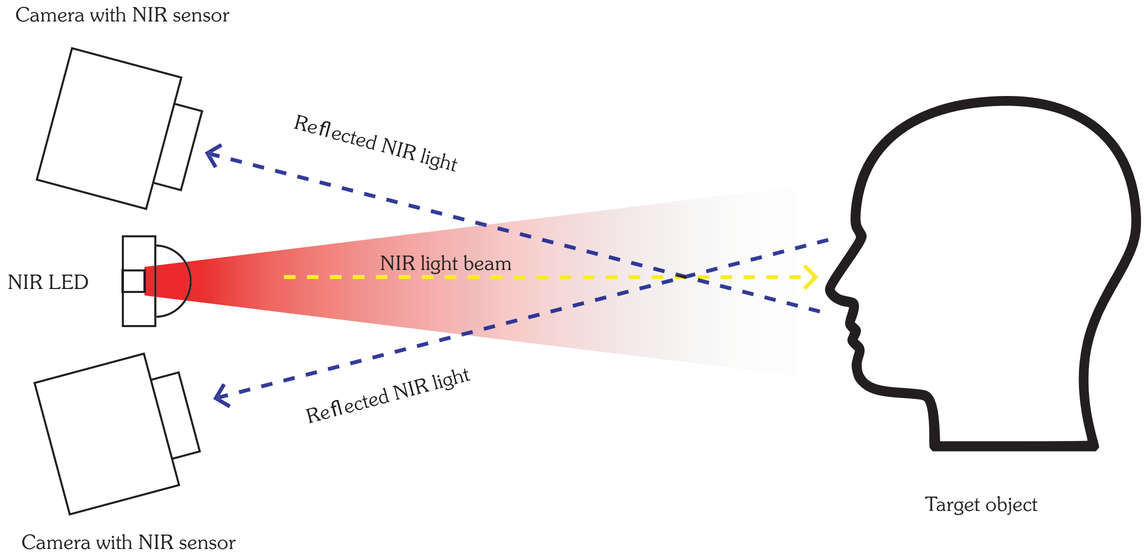

Fig. 8. A method based on stereovision in DMS systems using NIR LEDs (original design).

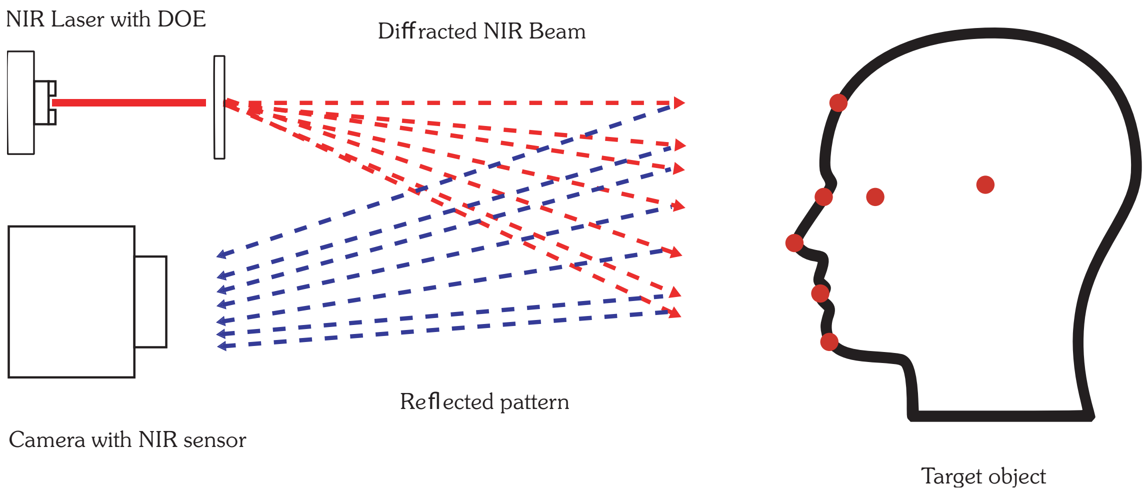

Fig. 9. Method based on measuring the distortion of the point/grid pattern in DMS systems using NIR Laser (original design).

face allows for the use of algorithms that can, for example, accurately determine the direction of the driver's gaze and head position.

CONCLUSIONS

The development of new optoelectronic components has enabled their use in the modern DMS systems, which are increasingly applied in the automotive industry. The further development of DMS systems will involve, among other things, the addition of an NPU (Neural Processing Unit) processor to cameras to support image processing with artificial intelligence (AI) algorithms [13]. The inclusion of an NPU processor in DMS cameras will significantly speed up image processing, enabling the use of more advanced AI algorithms, such as neural networks. This will allow for the analysis of facial expressions, eye movements, and other ocular parameters of the monitored driver during vehicle operation.

Car manufacturers, by equipping new vehicles with DMS systems, give drivers the option to partially or completely deactivate the system. Many drivers completely disable the DMS in their vehicles, justifying this decision by stating that, in their opinion, the system does not always correctly recognize signs of distraction or fatigue. Some drivers report that the DMS sometimes misinterprets their behavior, for example, detecting fatigue when they blink or warning about distraction when adjusting settings such as the vehicle's air conditioning. Another group of drivers, in disabling the DMS, is motivated by a reluctance to have their behavior monitored while driving, as well as concerns about privacy issues.

Therefore, in order for DMS systems to gain widespread acceptance among drivers and effectively contribute to increasing road safety, it is necessary to continue improving the control algorithms and gradually build user trust in these systems. This can also be achieved through educational and informational activities, for example, during driver's license courses.

AUTHORS' DECLARATION:

Study Design: Marcin Piotrowski, Łukasz Dziuda, Paulina Baran. **Manuscript preparation:** Marcin Piotrowski, Łukasz Dziuda, Paulina Baran. The Authors declare that there is no conflict of interest.

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