This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics

Design and Implementation of a Drowsiness -Fatigue-Detection System Based on Wearable Smart Glasses to Increase Road Safety

Wan-Jung Chang, *Member*, *IEEE*, Liang-Bi Chen, *Senior Member, IEEE*, and Yu-Zung Chiou, *Member*, *IEEE*

***Abstract*—This paper proposes a drowsiness-fatigue-detection (DFD) system based on wearable smart glasses to increase road safety. The proposed system is composed of a pair of wearable smart glasses, an in-vehicle infotainment (IVI) telematics platform, an on-board diagnostics (OBD)-II-based automotive diagnostic bridge, an active vehicle rear light alert mechanism, and a cloud-based management platform. A dedicated miniature bandpass IR light sensor is also proposed and implemented for the low-cost, lightweight, wearable smart glasses, which can provide a higher signal-to-noise ratio (SNR) than a general commercial infrared (IR) light sensor, minimize the ambient environmental light image, and efficiently increase the accuracy of detection. The proposed system can detect the status of the vehicle driver with respect to drowsiness or fatigue conditions in real time. When drowsiness or fatigue is detected, the active vehicle real light alert mechanism will automatically be flickered to alert following vehicles. The related information will also be concurrently transmitted to a cloud-based management platform. As a result, the proposed system can lead to increased road safety.**

***Index Terms*—advanced driver assistance system (ADAS), drowsiness-fatigue-detection (DFD) systems, Internet of Things (IoT), road safety, wearable devices.**

I. Introduction

THE number of vehicles is rapidly increasing, and this trend has led to an increased number of vehicle accidents. The National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System Encyclopedia [1] found that approximately 55,926 vehicles were involved in vehicular accidents in the United States in 2007. Moreover, 9,979 vehicle collision accidents were due to driver fatigue and inattention [1], [2] in 2007, as shown in Table I. The NHTSA's National Center for Statistics and Analysis also provided a brief statistical summary report [3] indicating that 416,000 accidents were caused by drowsy driving between 2005 and 2009.

TABLE I
Total Vehicle Collisions due to Fatigue and Inattention in the United States [1], [2]

Year	Total Vehicle Collisions	Number of Collisions Due to Fatigue and Inattention	Collisions Due to Fatigue and Inattention (%)
2007	55,926	9,979	17.5
2006	58,094	9,837	16.9
2005	59,495	8,949	15.0
2004	58,729	9,122	15.5
2003	58,805	8,835	15.0

Traffic vehicle accidents cause many injuries and deaths every day around the world. For instance, the NHTSA stated that approximately 1,500 people were killed in traffic accidents in 2002. Furthermore, there were 71,000 injuries resulting from the 100,000 collisions between 1989 and 1992 [4].

As shown in Table I, approximately 16% of collisions were related to fatigue and inattention. Thus, fatigue and inattention represent a major reason for vehicle crashes. A global status report on road safety from the World Health Organization (WHO) [5] also predicted that road traffic injuries will become the 5th-leading cause of death by 2030.

Drowsiness-fatigue-detection (DFD) systems have been widely studied and developed to avoid or reduce the occurrence of vehicle accidents [2], [6]-[22]. Although many related DFD systems have been developed, these DFD systems are passive, and active DFD systems have still not been developed.

Furthermore, many previous studies have used heavy computer-based systems [2], [6], which are not suitable or satisfactory for consumers in the real world. Moreover, image/video recognition-based DFD systems are not suitable for night driving due to insufficient lighting sources.

To address this situation, this study proposes an active DFD system that automatically implements related road-safety procedures. The proposed system uses a pair of wearable smart

Manuscript received March 30, 2018; revised June 8 2018 and August 12 2018; accepted September 3, 2018.

This work was supported in part by the Ministry of Science and Technology (MoST), Taiwan, R.O.C., under Grants, MOST 106-2622-8-218-001-TE2, MOST 106-2218-E-218-004, MOST 106-2632-E-218-002, and MOST 107-2632-E-218-001. An earlier and briefer version of this paper was presented at the 2018 IEEE ICCE [23] and the 2016 IEEE GCCE [30]. *(Corresponding author: Wan-Jung Chang.)*

W.-J. Chang is with the Department of Electronic Engineering, Southern Taiwan University of Science and Technology, Tainan 71005, Taiwan, R.O.C. (e-mail: allenchang@stust.edu.tw)

L.-B. Chen is with the Department of Electronic Engineering, Southern Taiwan University of Science and Technology, Tainan 71005, Taiwan, R.O.C. (e-mail: liangbi.chen@gmail.com)

Y.-Z. Chiou is with the Department of Electronic Engineering, Southern Taiwan University of Science and Technology, Tainan 71005, Taiwan, R.O.C. (e-mail: yzchiou@stust.edu.tw)

glasses as the main medium to detect the driver's drowsiness and fatigue to increase road safety.

The remainder of this paper is organized as follows. In Section II, previous works on DFD systems are reviewed. The proposed system is introduced in Section III. The prototype and its related experiments are presented in Section IV. Finally, in Section V, the conclusions of this work are outlined, and directions for future work are discussed.

II. Related Works

Recently, information and communications technologies (ICTs) and Internet of things (IoT) techniques for DFD systems have widely been discussed, studied, and developed [2], [6]-[22], [30]-[37].

A related overview, survey, and review of DFD systems can be found in Chacon-Murguoa and Prieto-Resendiz's full survey of DFD systems and related supporting techniques [2]. Koesdwiady *et al.* [6] presented an overview of the state of the arts and challenges of driver safety monitoring systems, including driver inattention, driver distraction, and driver fatigue. The taxonomy of driver safety monitoring systems has also been developed and discussed.

Choudhary *et al.* [7] surveyed drowsiness detection and alarm warning systems for drivers. They divided drowsiness detection techniques into five classifications: image processing-based detection, electroencephalography (EEG)-based detection, artificial neural network (ANN)-based detection, vehicular-based measures, and subjective measures.

Shi *et al.* [8] reviewed approaches for fatigued driving detection. They noted that future research on fatigued driving detection will focus on computer vision, deep learning, and data fusion. Sahayadhas *et al.* [9] reviewed and discussed the sensing techniques for detecting the drowsiness of a driver. Several measurements (e.g., physiological, behavioral, vehicle-based, and subjective methodologies) were adopted to detect drowsiness. The authors explained the advantages and disadvantages of each measurement.

Kaplan *et al.* [10] comprehensively surveyed and categorized the driver behavior analysis techniques for safe driving. They stated that driver drowsiness and distraction were the main causes of traffic accidents. In addition, they proposed a concept of vehicle-to-vehicle (V2V) communication-based driver behavioral dissemination that could be developed for the next generation of safe driving.

Rodríguez-Ibáñez *et al.* [11] analyzed more than 100 hours of driving in a real environmental case study. They also proposed a 3-phase drowsiness detection approach with several parameters, such as percentage eye openness tracking (PERCLOS), electroencephalography (EEG), and related behaviors.

For DFD system development, many methodologies have used physiological information. Zhang *et al.* [12] presented a fatigue-detection system that employed a wearable EEG-based device to monitor and train driver vigilance in order to achieve the high-speed training of a driving safety system. The presented system was composed of a wireless wearable EEG device, a trained driver vigilance detection mechanism, and an early-warning device. The experimental results demonstrated that the minimum testing time that can meet the real-time requirement of their high-speed training system is 2.16 s.

Awais *et al.* [13] proposed a hybrid methodology that combines the benefits of EEG and electrocardiography (ECG) to improve the performance of driver drowsiness detection. In this work, they extracted the features of the EEG, namely, the frequency domain's absolute and relative powers and the time domain's statistical and complexity measurements. They also extracted the ECG features, including the heart rate (HR) and heart rate variability (HRV). The performance of their proposed hybrid methodology reached 80.90%

Victoreia *et al.* [14] proposed an eye-tracking driver fatigue monitoring and warning system that allows the driver's status to be measured by the person's eye closure rate while driving. Moreover, an alert will be sounded when the driver is suspected to be sleeping.

Several approaches have adopted existing mobile devices or IT products. Galarza *et al.* [15] used a smartphone as a small computer. A mobile application of a human computer interaction (HCI) system was implemented to detect drowsiness using the most relevant visual indicators (including the lateral and frontal assent of the head, yawns, and the behaviors of eyes) to reflect the driver's current condition.

Chang *et al.* [16] implemented a smartphone-based driver assistance system that adopted front and rear cameras to identify the eyes, mouth, and face of the vehicle's driver. A warning voice is broadcasted when drowsiness is detected in the vehicle's driver. Moreover, this smartphone-based driver assistance system can also compute the distance between the vehicle in front and the vehicle's driver.

Kusuma Kumari [17] proposed a real-time driver drowsiness detection system that used a webcam to obtain video images of the driver. Several visual features (e.g., the eyes and mouth) were extracted using image-processing techniques to detect drowsiness. Wang *et al.* [18] proposed a three-tiered real-time networked service architecture to recognize the state of the driver to ensure safe driving.

Recently, some works have adopted popular artificial intelligence (AI) techniques (SVM or deep learning). Li and Chung [19] presented a driver drowsiness detection methodology that classifies alert and drowsy driving events using the wavelet analysis of HRV signals and a support vector machine (SVM) classifier. The SVM was trained by using eight fast Fourier transform (FFT)-based and wavelet-based features that were obtained from a 1-min HRV signal for four subjects. Their presented methodology achieved an accuracy of 95%.

Flores *et al.* [20] presented a real-time artificial intelligence (AI) visual information-based warning system that tracked and analyzed the eyes and face to determine a drowsiness index for automatically detecting driver drowsiness.

Reddy *et al.* [21] proposed a real-time deep learning-based drowsiness detector that was implemented on a GPU-based embedded system development board that achieved an accuracy of 89.5% with a three-class classification (normal, yawning, and drowsy) and a speed of 14.9 fps. In their work, a heavy baseline model for facial recognition was compressed to

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics

TABLE II
A COMPARISON BETWEEN DRIVER FATIGUE AND DISTRACTION DETECTION TECHNIQUES [10].

Method	Intrusive	Accuracy	Computational Cost	Robustness	Applicability	Success Rate (%)
EEG Signals	Yes	High	High	High	Low	80-98.2
Vehicle Movement	Yes	Low	High	Low	Medium	77-89.1
Head Movement	No	Medium	Low	Medium	Medium	77-97.5
Yawning Analysis	No	Medium	Low	Medium	Medium	80-91
Eye State Analysis	**No**	Medium	**Low**	**High**	**High**	**80-98.4**
Hybrid Solutions	Yes/No	High	High	High	High	N/A

TABLE III
A COMPARISON BETWEEN EYE STATE ANALYSIS-BASED APPROACHES AND THE PROPOSED SYSTEM.

Work	Sensors Adoption	Detection Device	Detection Objects	DFD Implementation	Special Features
Cyganek & Gruszczy ski [33]	Two IR images and LED	Dash-mounted Image System	Eyes	High-End Desktop/Laptop 64-bit Processors	Real-time hybrid visual system.
He *et al*. [34]	Front camera of a smartphone	Smartphone	Face & Eyes	Dual-Core Mobile 32-Bit CPU, SIMD Accelerator and a Dual-Core GPU	-
Shen *et al*. [35]	Video camera with IR illuminators	Dash-mounted Image System	Eyes	High End Desktop/Laptop 64-bit Processors	Pupil detection and yawning analysis in low light level environments.
BaHammam *et al.* [36] & Johns *et al*. [37]	Tiny IR transceiver	Wearable Smart Glasses	Eyes	Unknown Microprocessor	1) Can be adapted for prescription lenses. 2) Three different shades suitable for all driving conditions. 3) Lightweight.
Proposed System	Dedicated IR transceiver	Wearable Smart Glasses	Eyes	Low-End 8-Bit Microcontroller	1) Accessed and integrated with in-vehicle CAN bus signals via OBD-II Bridge. 2) Providing a cloud-based management platform. 3) Lightweight.

achieve a lightweight model on the GPU-based embedded system development board.

In the abovementioned previous works, powerful processors were needed to process the complex computations for the detection of drowsy/fatigue/sleep statuses.

On the other hand, Kaplan *et al.* [10] also compared related driver fatigue and distraction detection techniques by five criteria (intrusiveness, accuracy, computational cost, robustness, applicability, and minima-maximum success rate), as shown in Table II.

This comparison table pointed out that the eye state analysis-based method has many benefits, such as being nonintrusive and having low computational cost, high robustness, high applicability, and a higher minima-maximum success rate (accuracy).

Therefore, eye state analysis-based techniques should be a better methodology for detecting drowsy/fatigue/sleep statuses while meeting the requirements of being nonintrusive and having low computational cost, high robustness, high applicability, and a higher minima-maximum success rate (accuracy).

In general, eye closure duration will be increased when the driver is tired. In other words, eye blinking frequency will become slower for sleepy drivers. Generally, eye state analysis-based techniques are based on calculating value of PERCLOS. However, eye state analysis-based techniques have some limitations in obtaining those visual features [10]. They still encounter two major problems: improper lighting conditions and sunglasses. To overcome these problems, several previous works [33]-[37] adopted infrared (IR) imaging sensors. A comparison of eye state analysis-based approaches with the proposed system was made, as shown in Table III.

As can be seen in Table III, most of the previous eye state analysis-based approaches using mounted IR imaging sensors could not be applied and implemented in a low-cost lightweight wearable device to meet the requirements of general consumers. Hence, in this paper, a dedicated miniature bandpass IR light sensor is proposed and adopted to reduce complex computation and to achieve the operation of low-cost lightweight DFD wearable smart glasses without a powerful processor. Moreover, the proposed system can be accessed and integrated with in-vehicle CAN bus signals via an OBD-II Bridge, and a cloud-based management platform was developed to record and analyze drivers' DFD status.

III. THE PROPOSED SYSTEM

Fig. 1 shows an overview of the proposed system, which is composed of a pair of wearable smart glasses, an in-vehicle infotainment (IVI) telematics platform, and a cloud-based management platform. The proposed system is introduced in detail below.

A. *Wearable Smart Glasses*

The proposed wearable smart glasses are based on lightweight glasses that have several additional modules mounted onto them, including an IR sensor module (integrating a miniature IR LED (transmitter) with the proposed miniature bandpass (BP) IR light senor (receiver) [23]), a microcontroller (MCU), a battery-charging module, a memory module, and a

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics

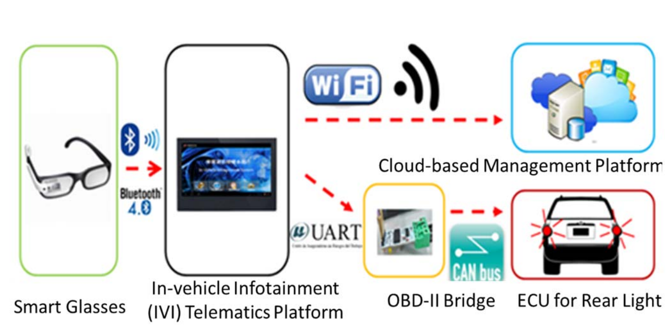


Fig. 1. Overview of the proposed system.

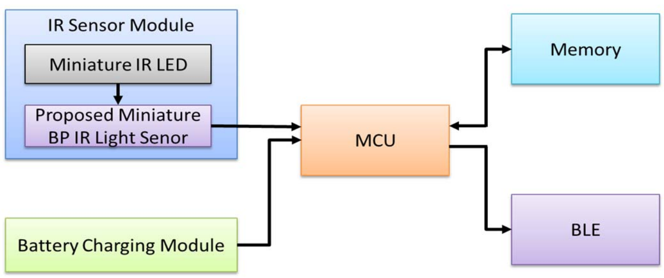


Fig. 2. Block diagram of the proposed wearable smart glasses.

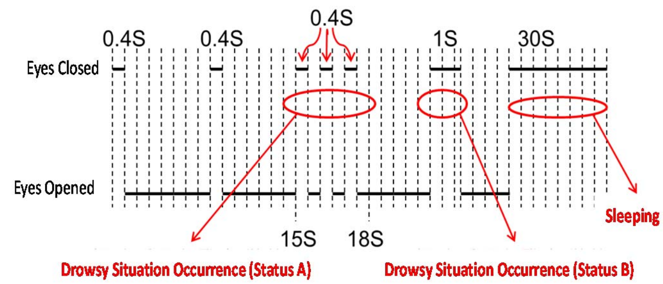


Fig. 3. Waveform for the status of the occurrence of drowsiness.

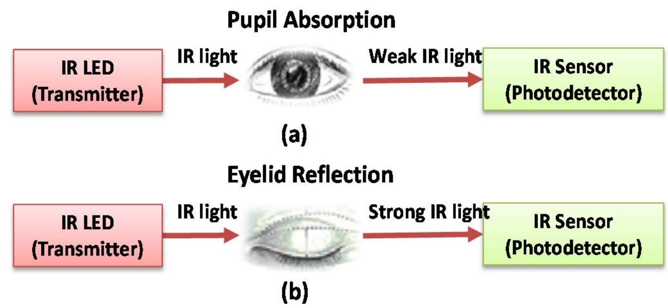


Fig. 4. IR light-based drowsiness-fatigue-detection based on different reflection conditions.

Bluetooth low-energy (BLE) wireless-communication module, as shown in Fig. 2.

The proposed wearable smart glasses are based on eye closures to detect the driver's drowsiness and fatigue. As a result, the miniature IR sensor transceiver that is mounted on the proposed wearable smart glasses continuously reads the voltage signal of the driver eyelids and transmits the voltage variables to the MCU.

1) Eye-based Drowsy/Sleep Detection Theory

As shown in Fig. 3, individuals typically take between 0.2 to 0.4 s to blink. Drowsiness can be detected when the time that the eyes are closed becomes very long, lasting longer than 1 to 2 s [19], [22]. If the eyes are closed for more than 30 s, an individual can be considered to be asleep.

Based on the abovementioned theory, in this paper, a pair of general commercial miniature IR transceivers can be adapted for detecting drowsiness and fatigue, as shown in Fig. 4. The different reflections are generated by the eyes' closure, and then, the IR light sensor (photodetector) is also transferred to the digital signal by integrating it with a data reader and an analog-to-digital converter (ADC) for the MCU processing.

2) Proposed Miniature Bandpass IR Light Sensor

The main problem with the use of a general commercial miniature IR transceiver is that the ambient environmental light image with more noise impacts the detection accuracy. Conversely, significant effort is required to filter these noises by using a powerful processor to achieve the required high detection accuracy.

Hence, the general commercial miniature IR transceiver is not suitable for installation on a pair of lightweight wearable smart glasses with high detection accuracy due to the limited processing ability of the MCU.

To overcome this problem, a miniature bandpass IR photodetector was designed and manufactured to detect IR light in the wavelength range of 810 to 890 nm. This photodetector does not interfere with the human eye or damage the retina.

The conventional miniature IR light sensor (photodetector) in the 850-nm wavelength range is typically fabricated with GaAs-based materials [24], [25]. The responsiveness of the sensor exhibited a broad-band characteristic similar to low-pass behavior. For the particular application considered in this paper, a narrow optical bandwidth is required to increase the SNR.

The structure of the proposed miniature bandpass IR light sensor is composed of five epitaxy layers, as shown in Fig. 5. When the wavelengths of the incoming light are shorter than 810 nm, the light is absorbed by the thick upper p-AlGaAs layer (~10% Al), and the active/absorption layer underneath (i-GaAs) is not illuminated.

Moreover, the proposed miniature bandpass IR light sensor does not respond to wavelengths greater than 890 nm (the absorption edge of i-GaAs). Hence, the tunable optical bandwidth and central wavelength of the sensor responsivity can be achieved by adjusting the Al mole fraction between the upper layer (p-AlGaAs) and the active/absorption layer (i-GaAs or i-InGaAs). Thus, the proposed miniature bandpass IR light sensor can sense a particular IR range, as shown in Fig. 6.

The advantages of the proposed miniature bandpass IR photodetector are providing a higher SNR, minimizing the ambient environmental light image and effectively enhancing the detection accuracy. As a result, the DFD recognition algorithm can be implemented more easily using a low-end MCU, such that it can be mounted on the low-cost, lightweight, wearable smart glasses with high detection accuracy.

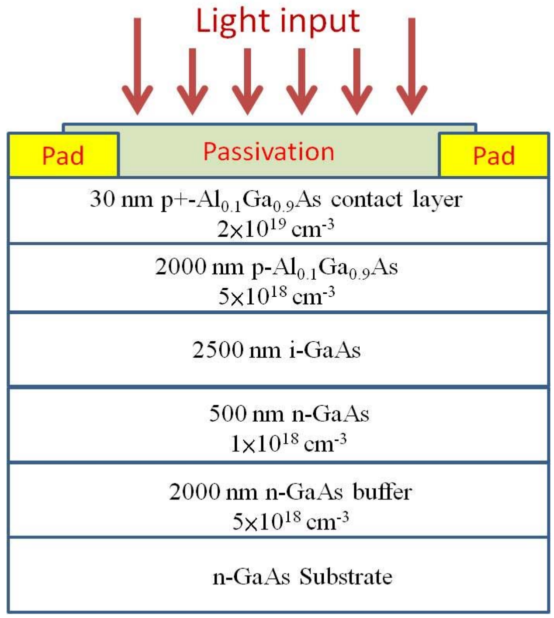


Fig. 5. Structure of the proposed miniature bandpass IR light sensor.

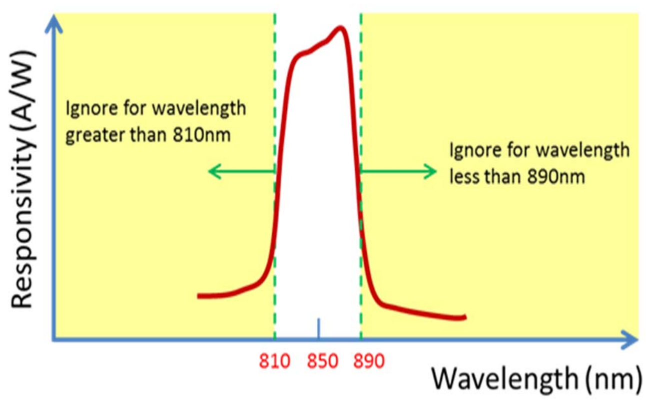


Fig. 6. Responsivity spectrum of the proposed miniature bandpass IR light sensor.

The proposed miniature bandpass IR photodetector must be able to measure different voltages between opening the eyes and closing the eyes for eye-based DFD recognition. Before the DFD recognition was developed, the miniature IR sensor transceiver needed to be mounted on the proposed wearable smart glasses.

Two subjects were randomly selected to test the output of the miniature IR sensor by opening their eyes for 1 s and then closing their eyes for 1 s. A total of six rounds of testing were performed, and two subjects were chosen to test the average voltage after thirty tests.

The average output voltage values after six rounds of measurement are shown in Table IV. The average voltage outputs of subjects A and B, who opened their eyes three times for 1 s, are expressed as V^{a}_{open} and V^{b}_{open}, respectively, and the average voltage outputs for when they closed their eyes three times for 1 s are expressed as V^{a}_{close} and V^{b}_{close}, respectively.

The experiment results in Table II illustrate that there is a certain gap between the voltages measured by the miniature IR

TABLE IV
MEASUREMENT TEST FOR THE MINIATURE IR SENSOR

	Round 1	Round 2	Round 3	Round 4	Round 5	Round 6
V^{a}_{open}	1.70	1.70	1.66	1.60	1.71	1.73
V^{b}_{open}	1.74	1.75	1.53	1.41	1.81	1.90
V^{a}_{close}	2.10	1.90	1.92	1.81	2.23	2.21
V^{b}_{close}	2.03	2.17	1.98	1.98	2.05	2.20

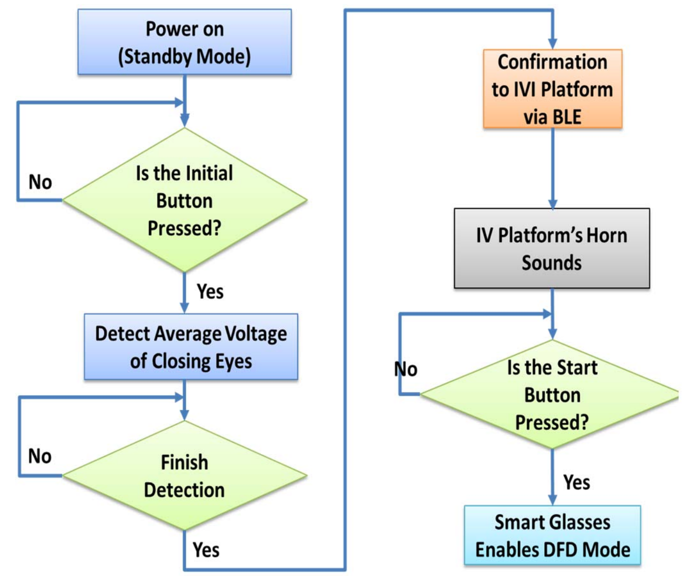


Fig. 7. Flowchart of the initial procedure (mode).

sensor transceiver when the subjects are opening and closing their eyes. The gap between these two points is approximately 0.01 to 0.05 V. Moreover, the measured voltage can change within 0.5 s from when the subjects open and close their eyes.

The proposed miniature bandpass IR light sensor has a good response speed, and it can be used to detect the opening and closing of the eyes. Hence, the proposed miniature bandpass IR light sensor can be applied to DFD recognition.

3) DFD Recognition

A firmware program was written in the low-end MCU of the proposed wearable smart glasses for DFD recognition. This DFD recognition firmware program has two main procedures (modes), the initial procedure (mode) and the DFD procedure (mode). The initial procedure (see Fig. 7) learns and records each driver's characteristics, including the facial surface's shape, the nose, and the pupils. Because each driver's face, nose, and pupils are different, it is impossible to use the same voltage value for the IR light sensor for all cases.

According to the open/closed-eye voltage test results (see Table II), the voltages read by the proposed miniature bandpass IR light sensor (photodetector) during the opening and closing of the eyes are relative pressure differences. Therefore, the initial procedure is required to learn and record each driver to achieve a higher DFD accuracy.

Fig. 8 shows the flowchart of the DFD procedure (mode). When the proposed wearable smart glasses enter the DFD mode, the driver's status of opening/closing eyes will be detected. Hence, when an inclination toward drowsiness and fatigue is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics

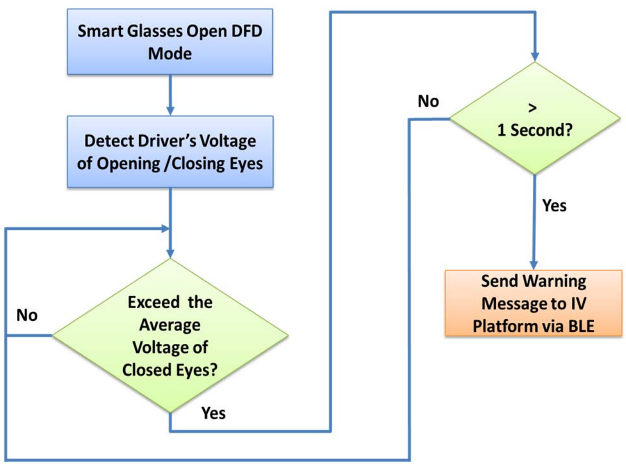


Fig. 8. Flowchart of the DFD procedure (mode).

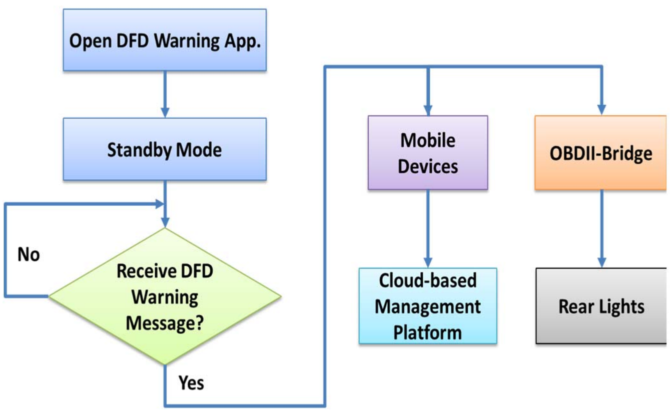


Fig. 9. Flowchart of the IVI telematics platform's operations.

detected (when the eyes are closed for more than 1 s), the DFD warning message will be sent to the IVI telematics platform via BLE.

B. In-Vehicle Infotainment (IVI) Telematics Platform

An application (App.) of the DFD warning was implemented using Java programming [26] and executed on the IVI telematics platform [38].

Fig. 9 shows the flowchart of the IVI telematics platform's operations. When the DFD warning App is opened, it will enter standby mode. Next, when the DFD warning message is received from the proposed wearable smart glasses via BLE communications, the related procedures will start automatically.

An example code of the DFD warning App is shown in Fig. 10. First, the serial (UART) port is used to communicate with the on-board diagnostics (OBD)-II-based automotive diagnostic bridge [27], [28] to execute CAN commands.

Next, when the DFD warning message is received from the proposed wearable smart glasses, the proposed IVI telematics platform will transmit a DFD warning command to the in-vehicle speakers and rear lights of the vehicle through an electronic control unit (ECU) via the CAN bus and the OBD-II-based automotive diagnostic bridge to signal the driver and the drivers of following vehicles.

Fig. 10. Example code of the DFD warning App.

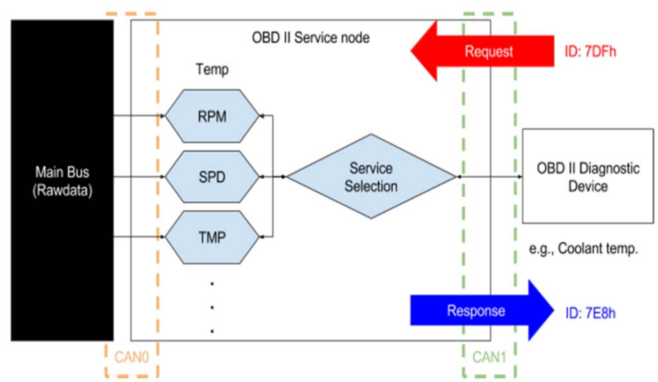


Fig. 11. Operational flow of an OBD-II-based automotive diagnostic bridge.

C. OBD-II-based Automotive Diagnostic Bridge

Fig. 11 shows the operation flow of an OBD-II-based automotive diagnostic bridge [27], [28], which is divided into a diagnostic mode and a CAN mode. In the diagnostic mode, the vehicle's information can be obtained by requesting that the device decode the request. In the CAN mode, the IVI telematics platform can issue CAN 2.0 commands to control the ECUs for the DFD warning.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics

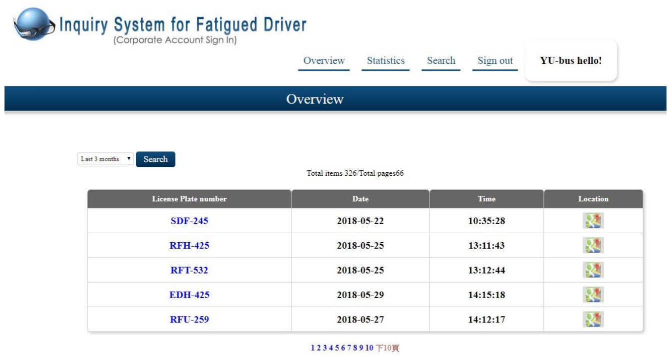


Fig. 12. Proposed cloud-based management platform for recording drowsiness and fatigue.

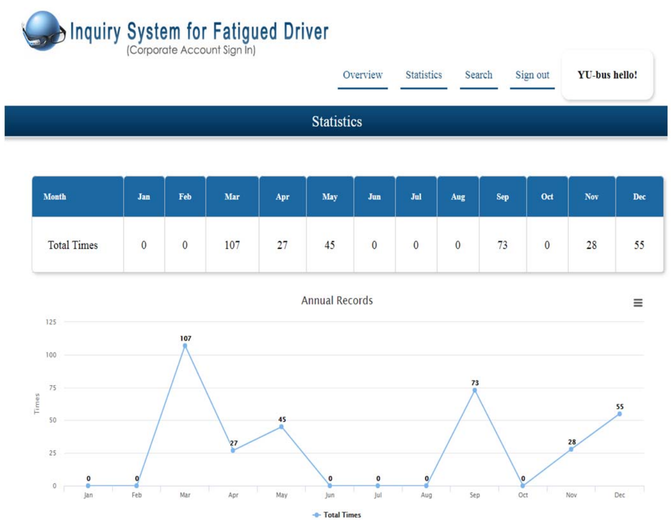


Fig. 13. Proposed cloud-based management platform for drowsiness and fatigue statistics.

Fig. 14. Photograph of the prototype of the proposed system.

Fig. 15. A pair of IR sensor modules is integrated with a miniature IR LED (transmitter). The proposed miniature bandpass (BP) IR light sensor (receiver) is mounted on the front of the wearable smart glasses.

For example, the OBD-II-based automotive diagnostic bridge is set to the CAN mode initially. When the drowsiness of the driver is detected by the proposed wearable smart glasses, the glasses will send a DFD warning message to the IVI telematics platform. Next, when the IVI telematics platform receives the DFD warning message, it will send a DFD warning command to the OBD-II-based automotive diagnostic bridge. The DFD warning command will be converted into a CAN 2.0 command via the OBD-II-based automotive diagnostic bridge to control the ECUs on the in-vehicle CAN bus. As a result, the in-vehicle speakers can generate tones and sounds to alert the driver. Moreover, the rear lights of the vehicle will also be flickered and controlled by the ECU via the CAN commands to alert the trailing drivers.

D. Cloud-based Management Platform

The cloud-based management platform is implemented by a server. The related information (e.g., vehicle license number, date, time, and location) can be automatically uploaded to the platform [29] via Wi-Fi or LTE, as shown in Fig. 12.

The goal of this platform is for it to be used as a service and management platform for passenger transportation companies to manage their own drivers' drowsy statuses or for an individual driver to monitor their personal drowsiness. As a result, passenger transportation operators can use this platform to check the date, time, and place of occurrences and the frequency statistics of drowsiness and fatigue (see Fig. 13) for each driver. Moreover, the passenger transportation operators can also use this platform to immediately execute suitable termination procedures for drowsy and fatigued drivers to increase road safety.

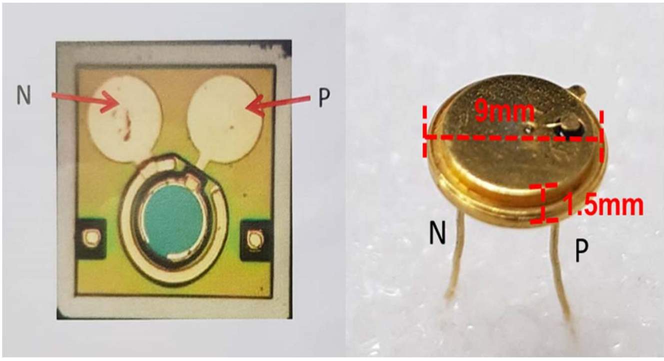
IV. Prototype and Experiments

A prototype of the proposed system is shown in Fig. 14. The demonstrated proposed system consists of the proposed wearable smart glasses (see Figs. 15 to 17), an IVI telematics platform (see Fig. 18), an OBD-II-based automotive diagnostic bridge, an in-vehicle speaker, the vehicle's rear lights, and a cloud-based management platform.

A pair of IR sensor modules is integrated with a miniature IR LED with the proposed miniature bandpass (BP) IR light sensor mounted on the front of the wearable smart glasses, as shown in Fig. 15.

A photograph of the prototype of the proposed miniature bandpass IR light sensor is shown in Fig. 16. A die photo of the proposed miniature bandpass IR light sensor is shown in Fig. 16 (a). A photodiode package photo of the proposed miniature

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCE.2018.2872162, IEEE Transactions on Consumer Electronics



(a) (b)

Fig. 16. Photograph of the prototype of the proposed miniature bandpass IR light sensor. (a) Die photo. (b) Photodiode package photo.

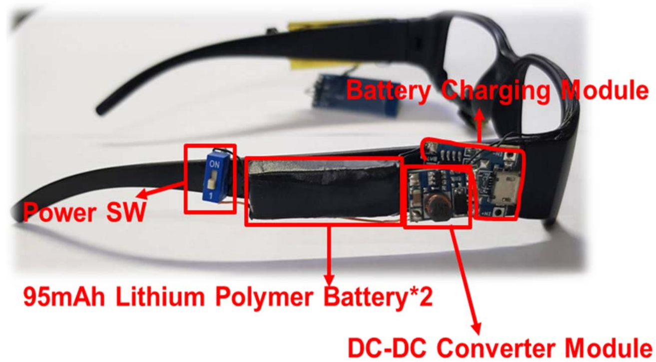


Fig. 18. Left-side implementation layout of the proposed wearable smart glasses.

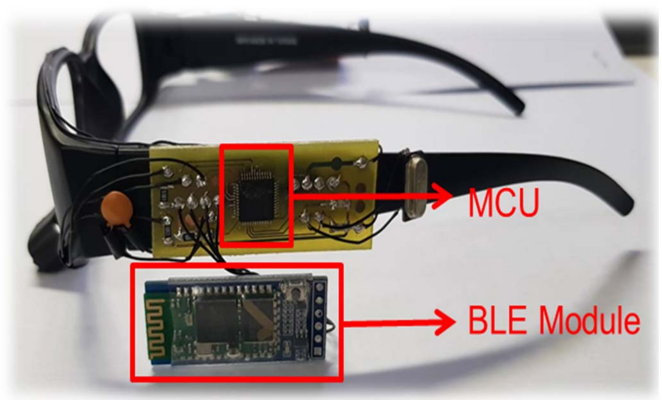


Fig. 17. Right-side implementation placement of the proposed wearable smart glasses.

Fig. 19. Photograph of the proposed IVI telematics platform installed on a vehicle.

bandpass IR light sensor is shown in Fig. 16 (b). The diameter of the proposed miniature bandpass IR light sensor is 9 mm, and the height of the proposed miniature bandpass IR light sensor is 1.5 mm.

The proposed miniature bandpass IR light sensor can be operated between “0” to “-5 V”, where the 850-nm wavelength can be set as the optimal response. The operating voltage is set at -5 V with a bandpass behavior in the wavelength range of 830 nm to 960 nm in this photodiode implementation.

The right-side implementation layout of the proposed wearable smart glasses, which contains an MCU with a built-in 10-bit ADC and a BLE-based wireless communication module, is shown in Fig. 17. The left-side implementation of the proposed wearable smart glasses, which includes a battery charging module, two 95-mAh lithium polymer batteries, a power switch, and a DC-to-DC converter module, is shown in Fig. 18.

A photograph of the proposed IVI telematics platform installed on a vehicle is shown in Fig. 19. When a DFD warning message is received from the proposed wearable smart glasses via BLE, a warning message will be triggered immediately and displayed on the screen of the proposed IVI telematics platform to alert the driver.

V. Conclusions and Future Work

A. Conclusions

In this paper, a wearable smart glasses-based DFD system was proposed to increase road safety. The proposed system consists of a pair of wearable smart glasses, an IVI telematics platform, an OBD-II-based automotive diagnostic bridge, an active vehicle rear light alert mechanism, and a cloud-based management platform to construct the active DFD system.

A miniature IR bandpass light sensor that can be mounted on the proposed wearable smart glasses was also proposed and fabricated. This IR bandpass light sensor was used to enhance SNR, minimize the ambient environmental light image, and efficiently increase the detection accuracy. In other words, this IR bandpass light sensor can be applied to effectively reduce the computing complex for low-end MCUs. As a result, the proposed wearable smart glasses are lightweight wearable devices that meet the requirements of consumers.

The results successfully demonstrated that the proposed system is a complete, wearable smart glasses-based DFD system. The proposed system can determine whether a driver is becoming drowsy and/or fatigued by wearing the proposed smart glasses. If drowsiness and fatigue are detected, a series of proactive reminders will be conducted, including through the

IVI telematics platform for the driver, the in-vehicle speakers for the driver, the rear lights being flicked for trailing vehicles, and the cloud-based management platform for related staff.

B. Future Works

Future work will consider the design, implementation and integration of the related low-power wide-area networks (WANs) with the proposed system to further increase road safety by adding vehicle-to-infrastructure (V2I) communications. Related AI techniques, such as deep learning, will be considered and applied to the proposed system to improve the active-based DFD system's abilities. Big-data analysis of driver behaviors may also be discussed and implemented using the proposed cloud-based management platform.

Acknowledgments

The authors would like to thank Prof. Chun-Kai Wang from the Department of Electronic Engineering at Southern Taiwan University of Science and Technology in Tainan, Taiwan, for supporting and assisting with the design, fabrication, and measurements of the 850-nm bandpass IR light sensor.

The authors also thank Prof. Jing-Jou Tang from the Department of Electronic Engineering at Southern Taiwan University of Science and Technology in Tainan, Taiwan, for supporting and assisting with the OBD-II Bridge and CAN bus-related techniques. The authors also thank Jorjin Technologies Inc. in New Taipei City, Taiwan, R.O.C., for the technical support and discussions regarding the wearable smart glasses.

References

[1] National Highway Traffic Safety Administration (NHTSA), "Fatality Analysis Reporting System Encyclopedia," [Online]. Available: https://www-fars.nhtsa.dot.gov/Main/index.aspx.

[2] M. I. Chacon-Murguia, and C. Prieto-Resendiz, "Detecting driver drowsiness: a survey of system designs and technology," *IEEE Consumer Electronics Magazine*, vol. 4, no. 4, pp. 107-119, Oct. 2015.

[3] National Highway Traffic Safety Administration (NHTSA)'s National Center for Statistics and Analysis, "A brief statistical summary: drowsy driving," *Traffic Safety Facts 2011*, Mar. 2011. [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/Publication/811449

[4] T. Moran, "Keeping Tired Drivers Alert, With No Snooze Button," *The New York Times*, March 11, 2007. [Online]. Available: http://www.nytimes.com/2007/03/11/automobiles/11WAKE.html?mcubz=1.

[5] World Health Organization (WHO), "Road traffic deaths index 2009 country rankings," Retrieved 2 Feb. 2010.

[6] A. Koesdwiady, R. Soua, F. Karray, and M. S. Kamel, "Recent trends in driver safety monitoring systems: state of the art and challenges," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 4550-4563, Jun. 2017.

[7] P. Choudhary, R. Sharma, G. Singh, and S. Das, "A survey paper on drowsiness detection & alarm system for drivers," *International Research Journal of Engineering and Technology (IRJET)*, vol. 3, no. 12, pp. 1433-1437, Dec. 2016.

[8] S.-Y. Shi, W.-Z. Tang, and Y.-Y. Wang, "A review on fatigue driving detection," in *Proceedings of the 4th Annual International Conference on Information Technology and Applications (ITA 2017)*, vol. 12, no. 01019, 2017, pp. 1-7.

[9] A. Sahayadhas, K. Sundaraj, and M. Murugappan, "Detecting driver drowsiness based on sensors: a review," *Sensors*, vol. 12, no. 12, pp. 16937-16953, 2012.

[10] S. Kaplan, M. A. Guvensan, A. G. Yavuz, and Y. Karalurt, "Driver behavior analysis for safe driving: a survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 6, pp. 3017-3032, Dec. 2015.

[11] N. Rodríguez-Ibáñez, M. A. García-González, M. Fernández-Chimeno, and J. Ramos-Castro, "Drowsiness detection by thoracic effort signal analysis in real driving environments," in *Proceedings of the 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEMBS'11)*, 2011, pp. 6055-6058.

[12] X. Zhang, J. Li, Y. Liu, Z. Zhang, Z. Wang, D. Luo, X. Zhou, M. Zhu, W. Salman, G. Hu, and C. Wang, "Design of a fatigue detection system for high-speed trains based on driver vigilance using a wireless wearable EEG," *Sensors*, vol. 17, no. 3, article 486, pp. 1-21, 2017.

[13] M. Awais, N. Badruddin, and M. Drieberg, "A hybrid approach to detect driver drowsiness utilizing physiological signals to improve system performance and wearability," *Sensors*, vol. 17, no. 9, article 1991, pp. 1-16, 2017.

[14] G. Victoreia, D. Yazhini, G. Parameswari, E. Gurumoorthi, and G. Vijayabarathy, "Driver fatigue monitoring system using eye closure," *International Journal of Modern Engineering Research*, vol. 4, no. 11, pp. 26-31, November 2014.

[15] E. E. Galarza, F. D. Egas, F. M. Silva, P. M. Velasco, and E. D. Galarza, "Real time driver drowsiness detection based on driver's face image behavior using a system of human computer interaction implemented in a smartphone," in *Proc. International Conference on Information Technology & Systems (ICITS'18)*, 2018, pp. 563-572.

[16] K. Chang, B.-H. Oh, and K.-S. Hong, "An Implementation of smartphone-based driver assistance system using front and rear camera," in *Proceedings of the 2014 IEEE International Conference on Consumer Electronics (ICCE'14)*, 2014, pp. 280-281.

[17] B. M. Kusuma Kumari, "A real time driver drowsiness detection system," *International Journal of Computer Applications*, no. 7, pp. 32-34, 2014.

[18] J. Wang, D. Liu, K. Zhang, X. Chen, and J.-U. Kim, "A novel real-time service architecture based on driver state detecting for improving road safety," in *Proceedings of the 2015 IEEE International Conference on Consumer Electronics – Taiwan (ICCE-TW'15)*, 2015, pp. 53-54.

[19] G. Li and W.-Y. Chung, "Detection of driver drowsiness using wavelet analysis of heart rate variability and a support machine classifier," *Sensors*, vol. 13, no. 12, pp. 16494-16511, 2013.

[20] M. J. Flores, J. M. Armingol, and A. de la Escalera, "Real-time warning system for driver drowsiness detection using visual information," *Journal of Intelligent & Robotic Systems*, vol. 59, no. 2, pp. 103-125, Aug. 2010.

[21] B. Reddy, Y.-H. Kim, S. Yun, C. Seo, and J. Jang, "Real-time driver drowsiness detection for embedded system using model compression of deep neural networks," in *Proceedings of the 2017 IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, 2017, pp. 1-8.

[22] V. Brodbeck, A. Kuhn, F. von Wegner, A. Morzelewski, E. Tagliazucchi, S. Borisov, C. M. Michel, and H. Laufs, "EEG microstates of wakefulness and NREM sleep," *NeuroImage*, vol. 62, no. 3, pp. 2129-2139. 2012.

[23] L.-B. Chen, W.-J. Chang, W.-W. Hu, C.-K. Wang, D.-H. Lee, and Y.-Z. Chiou, "A band-pass IR light photodetector for wearable intelligent glasses in a drowsiness-fatigue-detection system," in *Proceedings of the 2018 IEEE International Conference on Consumer Electronics (ICCE'18)*, 2018, pp. 676-677.

[24] S. D. Lin and C. P. Lee, "GsAs metal-semiconductor-metal photodetectors with low dark current and high responsivity at 850nm," *Semiconductor Science and Technology*, vol. 17, no.12, pp. 1261-1266, 2002.

[25] A. Karar, N. Das, C. L. Tan, K. Alameh, and Y. T. Lee, "High-responsivity plasmonics-based GaAs metal-semiconductor-metal photodetector," *Appl. Phys. Lett.*, vol. 99, pp. 133112, 2011.

[26] B. Kovacevic, M. Kovacevic, T. Maruna, and I. Papp, "A Java application programming interface for in-vehicle infotainment devices," *IEEE Transactions on Consumer Electronics*, vol. 63, no.1, pp. 68-76, Feb. 2017.

[27] H.-Y. Li, L.-B. Chen. W.-J. Chang, J.-J. Tang, and K. S.-M. Li, "Design and development of an extendable multi-protocol automotive gateway," in *Proceedings of the 2016 IEEE International Conference on Consumer Electronics – Taiwan (ICCE-TW'16)*, 2016, pp. 249-250.

[28] H.-Y. Li, J.-J. Tang, C.-T. Yu, W.-W. Hu, W.-J. Chang, D.-H. Lee, and Y.-C. Chung, "A novel hardware architecture of CAN applications," in *Proceedings of the 2017 IEEE International Conference on Consumer Electronics (ICCE'17)*, 2017, pp. 1-2.

[29] L.-B. Chen, H.-Y. Li. W.-J. Chang, J.-J. Tang, and K. S.-M. Li, "An intelligent vehicular telematics platform for vehicle driving safety supporting system," in *Proceedings of the 2015 IEEE International Conference on Connected Vehicles and Expo (ICCVE'15)*, 2015, pp. 210-211.
[30] L.-B. Chen, W.-J. Chang, J.-P. Su, J.-Y. Ciou, Y.-J. Ciou, C.-C. Kuo, and K. S.-M. Li, "A wearable-glasses-based drowsiness-fatigue-detection system for improving road safety," in *Proceedings of the 2016 IEEE 5th Global Conference on Consumer Electronics (GCCE'16)*, 2016, pp. 401-402.
[31] T. Danisman, I. M. Bilasco, C. Djeraba, and N. Ihaddadene, "Drowsy driver detection system using eye blink patterns," in *Proceedings of the 2010 International Conference on Machine and Web Intelligence*, 2010, pp. 230-233.
[32] M. Sabet, R. A. Zoroofi, K. Sadeghniiat-Haghighit, and M. Sabbaghian, "A new system for driver drowsiness and distraction detection," in *Proceedings of the 0th Iranian Conference on Electrical Engineering (ICEE2012)*, Tehran, Iran, May 15–17, 2012, pp. 1247–1251.
[33] B. Cyganek and S. Gruszczyński, "Hybrid computer vision system for drivers' eye recognition and fatigue monitoring," *Neurocomputing*, vol. 126, pp. 79-94, 2014.
[34] J. He, S. Roberson, B. Fields, J. Peng, S. Cielocha, and J. Coltea, "Fatigue detection using smartphones," *Journal of Ergonomics*, vol. 3, no. 3, p. 1-7, 2013.
[35] W. Shen, H. Sun, E. Cheng, Q. Zhu, Q. Li, and W. Shen, "Effective driver fatigue monitoring through pupil detection and yawing analysis in low light level environments," *International Journal of Digital Technology and its Applications (JDCTA)*, vol. 6, no. 17, pp. 372–383, 2012.
[36] A. S. BaHammam, S. Nashwan, O. Hammad, M. M. Sharif, and S. R. Pandi-Perumal, "Objective assessment of drowsiness and reaction time during intermittent Ramadan fasting in young men: a case-crossover study," *Behavioral and Brain Functions*, vol. 9, no. 1, Article 32, pp. 1-9, 2013.
[37] M. W. Johns, A. Tucker, R. Chapman, K. Crowley, and N. Michael, "Monitoring eye and eyelid movements by infrared reflectance oculograpgy to measure drowsiness in drivers," *Somnologie*, vol. 11, no. 4, pp. 234-242, 2007.
[38] M. Milosevic, M. Z. Bjelica, T. Marunam and N. Teslic, "Software platform for heterogeneous in-vehicle environment," *IEEE Transactions on Consumer Electronics*, vol. 64, no.2, pp. 213-221, May 2018.

Wan-Jung Chang (M'16) obtained a B.S in Electronic Engineering from Southern Taiwan University of Science and Technology, Tainan, Taiwan, R.O.C., in 2000; an M.S. in Computer Science and Information Engineering from National Taipei University of Technology, Taipei, Taiwan, R.O.C., in 2003; and a Ph.D. in Electrical Engineering from the National Cheng Kung University, Tainan, Taiwan, R.O.C., in 2008. He is currently an Associate Professor in the Department of Electronic Engineering at Southern Taiwan University of Science and Technology, Tainan, Taiwan, R.O.C. He is also a director of Artificial Intelligence over the Internet of Things Applied Research Center (AIoT Center) and Internet of Things Laboratory (IoT LAB) at Southern Taiwan University of Science and Technology, Tainan, Taiwan, R.O.C. He received the Best Paper Award at IEEE ChinaCom'09, the Best Paper Award at ICCPE'16, the 1st Prize of Excellent Demo! Award at IEEE GCCE'16/GCCE'17, and the First Prize Best Paper Award at IEEE ICASI'17. His research interests include cloud/IoT/AIoT systems and applications, protocols for heterogeneous networks, and WSN/high-speed network design and analysis. He is a member of the IEEE and the IEEE Consumer Electronics Society.

Liang-Bi Chen (S'04–M'10–SM'16) received B.S. and M.S. degrees in electronic engineering from the National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan, in 2001 and 2003, respectively. From 2004 to 2010, he was enrolled in the computer science and engineering Ph.D. program at the National Sun Yat-Sen University, Kaohsiung, Taiwan. He is currently pursuing a Ph.D. degree in electronic engineering at Southern Taiwan University of Science and Technology, Tainan, Taiwan. From August to September 2008, he had an internship with the Department of Computer Science, National University of Singapore, Singapore. He was also a Visiting Researcher with the Department of Computer Science, University of California, Irvine, CA, USA, from September 2008 to August 2009 and with the Department of Computer Science and Engineering, Waseda University, Tokyo, Japan, from July to August 2010. In May 2012, he joined BXB Electronics Co., Ltd., Kaohsiung, Taiwan, as an R&D Engineer. In May 2013, he was transferred to the position of Executive Assistant to the Vice President, which he held until September 2016. In October 2016, he joined Southern Taiwan University of Science and Technology, Tainan, Taiwan, as a senior technical manager and a part-time lecturer. He has also served as a TPC member, an IPC member, and a reviewer for many IEEE/ACM international conferences and journals. He was a recipient of the 2014 IEEE Education Society Student Leadership Award. He received the First Prize Best Paper Award at IEEE ICASI'17, the Honorable Mention Award at ICAAI'16, the 1st Prize of Excellent Demo! Award at IEEE GCCE'16/GCCE'17, and the 2nd Prize of Excellent Poster Award at IEEE GCCE'16. He is a senior member of the IEEE Consumer Electronics Society and a member of the IEICE and the PMI.

Yu-Zung Chiou (M'06) was born in Taiwan. He received B.S., M.S., and Ph.D. degrees from the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan, in 1997, 1999, and 2003, respectively. From 1999 to 2001, he worked at Taiwan Semiconductor Manufacturing Company (TSMC), Ltd., as an Engineer, specializing in CMOS image sensors and high-voltage devices. He is currently a Full Professor in the Department of Electronics Engineering, Southern Taiwan University of Science and Technology, Tainan, where he was named Manager of the Optoelectronics and Microwave Device Laboratory. He has authored over 60 papers in thin-film materials and optoelectronic devices. His current research interests include optoelectronic devices of III–V compound semiconductors. He is a member of the IEEE.