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Driver ECG Measuring System With a Conductive Fabric-Based Dry Electrode

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ABSTRACT The dry electrodes that the automotive manufacturers use to measure electrocardiogram (ECG) signals for driver status monitoring have three technical problems: a lack of attachment flexibility, low ECG signal detection stability, and the potential to harm or irritate the driver. In addition, the complicated signal-conditioning circuits employed by automotive manufacturers to improve the SNR, increase the ECG signal detection stability, and to ensure a wider dynamic range of the electrodes increase the cost and complexity of driver ECG measuring systems. In this paper, we propose a driver ECG measuring system that resolves these three technical issues using a steering wheel covered with a conductive fabric-based dry electrode material, which is manufactured by an electroplating method. In addition, we employ a conductive fabric-shaping procedure in the development of the fabric-based dry electrode to improve the attachment flexibility and to reduce the cost and complexity of the required signal-conditioning circuit. We verify the ECG signal-measuring performance of the proposed system by comparing it with ECG signal measurement results from a clinical ECG monitoring system. In addition, despite applying a simpler signal conditional circuit than those used in conventional ECG measuring systems, we verify that the proposed system achieves higher SNR and ECG signal detection stability than conventional ECG measuring systems through various field tests in actual driving environments.

INDEX TERMS Conductive fabric, dry electrode, driver monitoring system, contact-based ECG measuring system, ECG signals, conductive fabric shaping, steering wheel, smart car.

I. INTRODUCTION

The national highway traffic safety administration (NHTSA) classifies risky driving factors that cause traffic accidents into drunk driving, distracted driving, drowsy driving, no seat belt use, speeding, and drugged driving [1]. One interesting point is that except for the no seat belt uses and speeding classifications, all of the other factors are related to the driver's physiological condition.

Therefore, the development of driver status monitoring (DSM) systems using the driver's physiological signals, such as photoplethysmography (PPG), electrocardiogram (ECG), and electroencephalography (EEG), has become one of the major issues in recent smart car research. In particular, DSM systems that use ECG signals can measure the driver's physiological signals more stably and conveniently than systems using PPG and EEG signals [2], [3]. Owing to this advantage, automotive manufacturers such as BMW, Toyota and Daimler AG have been developing DSM systems which utilize the ECG signals of drivers [2]. In existing DSM systems, automotive manufacturers attach a dry electrode, which is either made of metal or manufactured via an electroless plating method to the steering wheel in an effort to improve the ECG signal detection stability [4].

BMW proposes a DSM system that measures the skin resistance of drivers regardless of the location of the driver's hands on the steering wheel, which in this case was wound with a conductive strip electrode [5], [6]. In those studies [5] and [6], BMW proved that a conductive strip electrode can obtain meaningful measurements approximately 81% of the time, whereas punctiform-type sensors, such as PPG sensors, obtain valid measurements at a rate of only 44% [5]. In collaboration with Denso, Toyota proposes an ECG measuring system that is robust to noise occurring in driving environments [7]–[10]. In two related studies [7] and [9], Denso attached a pair of chrome-coated metal-indifferent electrodes (length 535mm, width 7mm, and thickness 0.5mm) onto the left and the right sides of the steering wheel for the stable measurement of ECG signals. In other work [8], Denso proposed a noncontact-based ECG measuring system which uses capacitive sensing between the driver's body and sensor heads attached to the driver's seat. This system involves the attachment of a number of sensor heads to the backrest of the driver's seat. Also in that study [8], Denso showed that a combination of contact and noncontact approaches in a DSM system improves the SNR of ECG signals measured when the vehicle is driven. Daimler AG proposed a technique that measures the driver's ECG signals when driving using five brass electrodes, in this case metal-type dry electrodes, which are attached to the steering wheel [11]. In particular, Daimler AG applied an electrodermal activity (EDA) circuit for a signal-conditioning circuit [12] to improve the dynamic range of the electrode and the ECG signal detection stability when the driver drives the vehicle.

Despite these studies of DSM systems using ECG signals, ECG measuring systems still have several technical problems. First, a flexibility problem occurs when a metal-type dry electrode is attached to a curved steering wheel, which limits ECG signal acquisition when the dry electrode is attached only to limited locations of the steering wheel. Second, poor ECG signal detection stability can arise, caused by the changing surface resistance of the dry electrode [13], Third, harm or irritation to the human body can be caused by skin contact with harmful metal substances, such as chrome, which can be plated onto the surface of the metal of the dry electrode [14], [15]. To resolve these technical problems, the dry electrode used to measure the ECG signals should satisfy the following conditions. First, it should be flexible enough to be stably attached to the steering wheel rim. Second, consistent surface resistance of the dry electrode should be maintained across the entire surface of the steering wheel for stable ECG signal acquisition. Finally, there should be no segregation of the conductive materials plated onto the dry electrode in order to prevent harm and/or to mitigate irritation to the human body.

This paper addresses these three technical problems and proposes a steering wheel covered with a conductive fabric-based dry electrode (dry electrode, in short) that measures ECG signals stably when the vehicle is driven. In general, the conventional clinical electrodes used in ECG measuring systems are classified as the gel electrode and dry electrode types [16], [17]. Given the good signal quality of gel electrodes, they are mostly used as clinical electrodes. However, gel electrodes can cause skin rashes when used for long period of times, and they require a preparation processes, such as skin shaving and cleansing [17]. To overcome this disadvantage, researchers have tested a number of materials for dry electrodes, such as stiff electrodes, soft and flexible material-based electrodes, and fabric electrodes [17]. This paper exploits the fabric electrode among all of the conventional dry electrodes used in clinical ECG measuring systems. For the first time, we apply a fabric electrode to a driver ECG measuring system and develop a dry electrode using an electroplating method. The proposed dry electrode can resolve or significantly alleviate all of the aforementioned problems, i.e., attachment flexibility, ECG signal detection stability and potential harm or irritation to drivers. In addition, we employ a conductive fabric-shaping procedure that enables the developed dry electrode to be tightly attached to a round steering wheel without creasing, while enhancing the adhesiveness of the dry electrode. Moreover, the conductive fabric-shaping procedure produces stable contact between the driver's palm and the dry electrode attached to the steering wheel. As a result, despite applying a simpler signal conditional circuit than those used in conventional ECG measuring systems [3], the proposed ECG measuring system can measure ECG signals with high levels of stability, and it shows higher SNRs of the measurements. Below, we describe the development procedure of the dry electrode with emphasis on the conductive fabric-shaping procedure as employed in this paper.

In addition, we measure and analyze the ECG signals of drivers in idling and driving states to demonstrate the performance of the proposed system. We verify the static performance of the proposed system by comparing the ECG signals measured by the proposed system in an idling state with the ECG signals measured by a clinical ECG measuring system. In addition, we demonstrate the dynamic performance through an analysis of ECG signals measured with the proposed system in various driving environments, such as straight driving, driving over speed bumps, and changing lanes while driving.

This paper has contributions and novelty to

- Propose a driver ECG measuring system that resolves three technical issues, such as a lack of attachment flexibility, low ECG signal detection stability, and potential to harm or irritate the driver, using a steering wheel covered with a conductive fabric-based dry electrode material which is manufactured by an electroplating method. Developed electrode provides higher SNR and ECG signal detection stability than conventional ECG measuring systems despite applying a simpler signal conditional circuit than those used in conventional ECG measuring systems.
- Measure and analyze the ECG signals of drivers in idling and driving states to demonstrate the dynamic performance through an analysis of ECG signals measured with the proposed system in various driving environments.

This paper is organized as follows. In section 2, we introduce the development procedure of the proposed conductive fabric-based dry electrode, which can resolve the three aforementioned technical problems (lack of attachment flexibility, lack of ECG signal detection stability and harm or irritation to the driver) which thus far previous studies have failed to address. We also explain in detail the conductive fabric-shaping procedure that provides a stable contact surface between the dry electrode and the driver's palm. In section 3, we explain the signal-conditioning circuit developed here, which is utilized to acquire the driver's ECG signals reliably. Section 4 demonstrates the performance of the proposed system through various field tests in actual driving environments. Finally, we conclude the paper in Section 5.

II. PROPOSED CONDUCTIVE FABRIC-BASED DRY ELECTRODE

While ECG signals are very fine and weak at the millivolt level [16], driving environments can add various strong noises [7]. Therefore, automotive manufactures have developed ECG measuring systems which use dry electrodes made of metal or which rely on an electroless plating method to improve the ECG signal detection stability [5]–[11]. However, the ECG measuring systems developed by automotive manufacturers have the following disadvantages. First, the ECG signal detection stability is degraded due to the increased dry electrode surface impedance caused by the dryness of the electrode when exposed to air. Second, the flexibility of the dry electrode is degraded due to the thick metal film which forms on the surface of the dry electrode [13]. Finally, harm or irritation to the driver can arise due to the separation of the metal substances plated onto the dry electrodes [14], [15]. Thus, in this section, we propose a conductive fabric-based dry electrode (dry electrode, in short) which is developed using an electroplating method to resolve these three technical problems simultaneously. For the first time, we apply the fabric electrode [17] of the type used in clinical ECG measuring systems to a driver ECG measuring system. We explain in detail the conductive fabric-shaping procedure employed here for the wrapping of the steering wheel rim with the developed dry electrode without creasing. In addition, we verify the completeness of the developed dry electrode through field-emission scanning electron microscopy (FE-SEM) and an energy dispersive x-ray (EDX) analysis.

A. DEVELOPMENT OF THE CONDUCTIVE FABRIC-BASED DRY ELECTRODE USING AN ELECTROPLATING METHOD

The proposed dry electrode is developed by electroplating AgCl onto fabric. In this paper, we select polyester as the fabric. Generally, the targets for electroplating are conductive materials [18]; however, the fabric used as the target of electroplating in this paper has no conductivity. Therefore, before we electroplate the AgCl onto the fabric to implant conductivity, we impregnate the fabric with a thin layer of Ag, which results in an Ag-impregnated fabric. Subsequently, we tightly wrap the wet Ag-impregnated fabric around the rim of the steering wheel to match the shape of the steering wheel, subsequently hardening the Ag impregnated onto the fabric in the shape of the steering wheel by natural and hot-air drying, resulting in a shaped fabric. Finally, we complete the process of developing the dry electrode by applying the electroplating method to the shaped fabric. In this subsection, we describe the process of developing the dry electrode with an emphasis on the conductive fabric-shaping procedure.

We divide the development procedure of the dry electrode into six steps: cleaning, agitation, impregnation, shaping, drying, and electroplating. In the cleaning step, we clean the surface of the fabric to impregnate the fabric evenly with Ag, a conductive substance. The detailed procedure is described below. 1) Removal of foreign substances on the surface of the fabric using a surfactant. 2) Natural drying of the cleaned fabric in the shade for three hours. 3) Forced drying for 60 minutes in an $80°C$ hot air drying chamber after fixing the fabric flat without shrinkage. Note that natural and hot-air drying are performed in this step to maximize the impregnation of Ag.

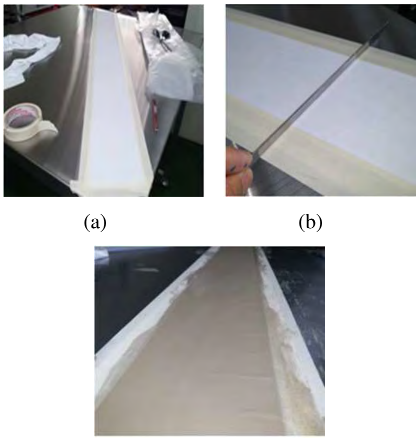
The agitation step serves to dilute the Ag paste with a diluent, making it possible to impregnate the cleaned fabric uniformly with Ag paste. Fig. 1 shows the agitation of the Ag paste with the diluent using an agitator (Fig.1(a)) and the diluted-Ag (Fig.1(b)) [19].

(a) (b)

FIGURE 1. Agitation of the Ag paste. (a) Agitation of the Ag paste with the diluent. (b) Diluted-Ag.

In general, the target for electroplating is a conductive material [18]; however, the target (i.e., the fabric in this paper) here has no conductivity. Thus, during the impregnation step, we impregnate the cleaned fabric with the diluted-Ag before the electroplating step. Note that during the impregnation procedure, if the Ag impregnated into the surface of the fabric is thick, the flexibility of the conductive fabric is degraded when the diluted Ag hardens on the fabric. Therefore, the diluted-Ag must be impregnated very thinly on the cleaned fabric for the minimum conductivity required to utilize the electroplating method. The impregnation procedure proceeds as follows. 1) Fix the cleaned fabric to the work table using paper tape to create a thin Ag-film layer on the fabric, as shown in Fig. 2(a). 2) Impregnate the fabric with the diluted-Ag by painting the diluted-Ag onto the fabric. We impregnate the cleaned fabric with the diluted-Ag evenly and thinly through a repeated metal squeezing step, as shown in Fig. 2(b). Fig. 2(c) shows the Ag-impregnated fabric. Because the Ag-impregnated fabric before Ag hardening has elasticity, we need to shape the Ag-impregnated fabric into the shape of a steering wheel before the Ag hardens.

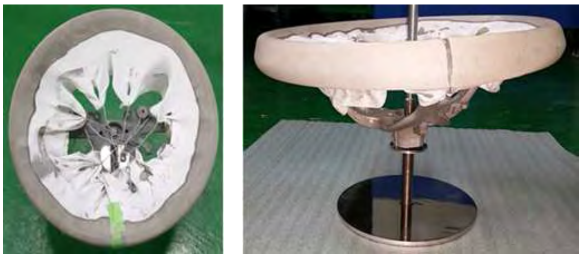
Therefore, the shaping step must be performed before the drying step, during which the Ag that is impregnated the fabric is hardened. The shaping procedure is as follows: 1) Wrap the Ag-impregnated fabric from the edge of the steering wheel in a wet condition. 2) Fasten the fabric around the rim tightly by binding both edges of the fabric to the center of the rim. Fig. 3 shows the shaped fabric.



(a) (b)

(c)

FIGURE 2. Ag-impregnation step of the fabric. (a) Fabric setting. (b) Metal squeeze. (c) Ag-impregnated fabric.



(a) (b)

FIGURE 3. Conductive fabric-shaping procedure. (a) Top view. (b) side view.

The drying step hardens the Ag onto the shaped fabric to solidify the shape and vaporizes any unnecessary diluent which was added to the shaped fabric during the impregnation step, as shown in Fig. 3. Thus, the shaping and drying steps are important to ensure that the dry electrodes have a smooth and even contact surface without creasing. The drying procedure is as follows. 1) Dry the shaped fabric at a low temperature of $80°C$ for 60 minutes to remove any air bubbles created during the impregnated step. 2) Dry the low-temperature dried and shaped fabric at $140°C$ (the firing temperature of the Ag paste) for 120 minutes to vaporize the diluent added to the Ag-impregnated fabric, which results in hardening only the Ag in the shaped fabric. After this step, we can remove impurities remaining on the surface of the shaped fabric through surface cleaning using an ultrasonic cleaner with methylethylketone. With this setup, the shaped fabric is hardened in the shape of a steering wheel, which results in the dried fabric.

Note that the dried fabric maintains the shape of the steering wheel after the drying step. Therefore, we can electroplate AgCl onto the dried fabric surface without deformation. In the electroplating step, the AgCl forms a thin AgCl film on the surface of the dried fabric because it is quickly plated onto the surface of the dried fabric in a short period of time. As a result, the dried fabric turns into a dry electrode while maintaining elasticity, which is the original property of the fabric (polyester). This, this step enhances the attachment flexibility of the developed dry electrode. The electroplating procedure is as follows. 1) Completely immerse the dried fabric in the Cl electrolyte and then connect a (+) power line to the dried fabric. 2) After immersing the Ag-metal bar in the electrolyte, connect a ground power line to the Ag-metal bar. 3) Supply 7.5V at 6.5A for ten minutes. As a result, the dried fabric turns into the conductive fabric-based dry electrode (dry electrode, in short), as shown in Fig. 4(a).

The conductivity of the developed dry electrode affects the ECG signal detection stability in the driving environment, which introduces strong noise. Thus, the AgCl electroplated onto the developed dry electrode should be uniformly and firmly hardened on the dry electrode in order to maintain high conductivity. We verify the completeness of the developed dry electrode using FE-SEM and EDX analyses. Fig. 4(b) shows the FE-SEM analysis result of the dry electrode. Here, dark grey signifies the fabric (polyester) tissue and light grey represents the AgCl. This outcome shows that the AgCl component has uniformly penetrated into and stably hardened onto the dry electrode. Fig. 4(c) shows the EDX analysis results of the developed dry electrode. As shown, the developed dry electrode contains C and O, which are the main components of the fabric, in respective amounts of 40.06% and 30.9%, , while Ag and Cl components are present at amounts of 16.72% and 10.93%, respectively. This also shows that Ag has a higher density than Cl due to the fact that Ag that was impregnated into the fabric beforehand.

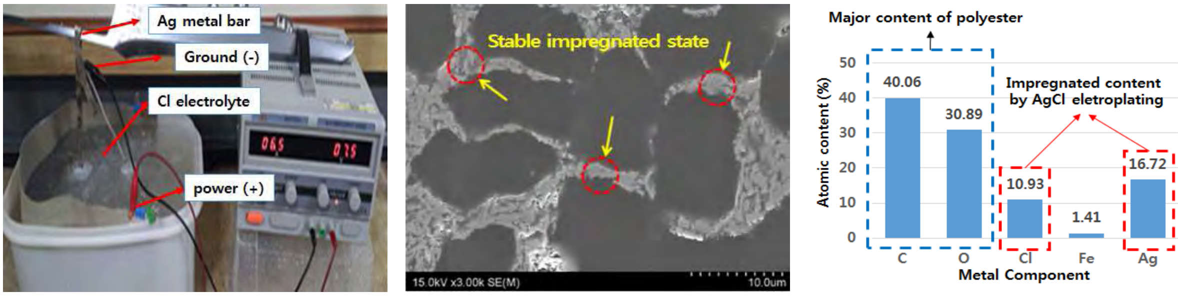
III. THE PROPOSED ECG MEASURING SYSTEM USING THE CONDUCTIVE FABRIC-BASED DRY ELECTRODE

The change of the surface impedance between the dry electrode attached onto the steering wheel and driver's hands grabbing the dry electrode affects the performance of the contact-based ECG measuring system [13]. Therefore, to improve the ECG signal detection stability, the developed conductive fabric-based dry electrode (dry electrode, in short) should be uniformly and tightly attached to the steering wheel rim. This section explains how the developed dry electrode is attached to the round steering wheel without creasing and explains the each part of the signal-conditioning circuit block utilized to acquire the reliable ECG signal of the driver during driving.

A. DEVISING THE DRY ELECTRODE ON A STEERING WHEEL

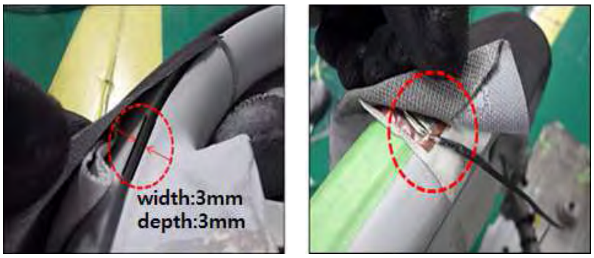
In general, at least two contact body points on the left and right sides of the heart [3] are required to measure ECG signals. Thus, in contact-based ECG measuring systems, at least two electrodes on the left and right sides of the steering wheel are used to maintain direct contact with both hands of the driver [3].

The following explains how the developed dry electrode on the surface of the steering wheel rim was realized. 1) Cut 3mm grooves along the front and rear sides of the rim. 2) Arrange the two dry electrodes clockwise and



(a) (b) (c)

FIGURE 4. AgCl electroplating procedure and the results. (a) AgCl electroplating procedure. (b) FE-SEM analysis result for the dry electrode. (c) EDX analysis result for the dry electrode.



(a) (b)

FIGURE 5. Adhesion between the dry electrode and steering wheel. (a) Adhesion between the dry electrode and the steering wheel rim. (b) Connecting the dry electrode to a copper plate.

FIGURE 6. The developed steering wheel with two conductive fabric-based dry electrodes.

counterclockwise from the 12 o'clock position to the 6 o'clock position of the rim without overlapping. 3) Push the dry electrodes into the 3mm grooves and adhere the dry electrodes onto the outer surface of the rim as shown in Fig. 5(a). 4) Insert a wiring contact into the dry electrodes using a copper plate, as shown in Fig. 5(b).

The inner side of the steering wheel rim, which is not wrapped by the dry electrode, can be wrapped by natural cowhide to enhance the driver's grip on the steering wheel. Fig. 6 shows the ECG measuring steering wheel covered by the developed dry electrode on the outer surface.

B. SIGNAL-CONDITIONING CIRCUIT

One ECG signal period consists of a P wave, a QRS complex, and a T wave [20]. In conventional DSM systems using ECG signals, the QRS complex is classified as the major component in the detection of the driver's condition, and various studies have been performed to detect the QRS complex from ECG signals [2], [3].

In practice, because ECG signals exist at the milli-volt level [16], the signal-conditioning circuit that separates ECG signals from strong noise is an essential part of a DSM systems which uses ECG signals. In general, a basic signal-conditioning circuit applied to a DSM system using ECG signals consists of an acquisition block and a filtering block, as shown in Fig. 7 [3]. To improve the ECG signal detection stability of DSM systems, automotive manufacturers add additional analogue signal-processing circuits to the basic signal-conditioning circuit. Ford [21] and Daimler AG [11] add an EDA circuit [12] to the 'In' point in Fig. 7 to increase the dynamic range of the dry electrode, while Denso adds a Driven Right Leg (DRL) circuit [22] to the 'Out' point in Fig. 7 to reduce common-mode input noise in the dry electrode 7 to reduce the common mode input noises in the dry electrode [8]. Despite several studies of signal-conditioning circuits, as the number of additional signal processing circuits increases, the DSM system has the following disadvantages: an increased cost of the overall signal-conditioning circuit, and increased complexity of the applied techniques.

The conductive fabric-based dry electrode (dry electrode, in short) introduced in this paper shows better performance in terms of flexibility for a stable attachment than the metal and dry electrodes introduced in the literature [8], [11], [21], [22]. For this reason, the ECG measuring steering wheel covered by the developed dry electrode provides stable contact between the driver's palm and the dry electrode attached to the steering wheel. Therefore, we utilize only a basic signal-conditioning circuit for stable ECG signal detection in the proposed system. It was found, that utilized signal-conditioning circuit reduces the cost and complexity of signal-conditioning. This subsection describes the basic signal-conditioning circuit utilized in the proposed system.

Fig. 7 shows a block diagram of the signal-conditioning circuit used here. The acquisition block measures the ECG signals from the driver's hands when the driver grips the steering wheel. In this block, we use an instrumentation amplifier (INA) with a high common-mode rejection ratio (CMRR) to amplify the measured ECG signals and to minimize the

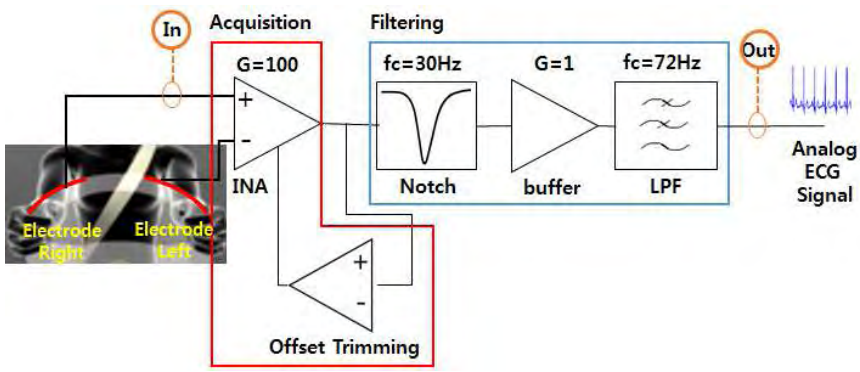


FIGURE 7. Block diagram of signal-conditioning circuit for ECG measuring system.

noise in the measured ECG signals at the same time. We apply TI's INA 116 [23], an ultra-low-input bias current instrumentation amplifier with a minimum CMRR of 86dB in the entire frequency domain with a gain of 100 [V/V]. In addition, we use an offset trimming circuit to minimize the offset voltage in the INA output and to secure a high CMRR [23]. Note that the INA applied in the proposed system is used in multiple techniques in the literature [8], [11], [21].

The filtering block reduces the input noise in the ECG signals after the INA. The filtering block consists of a notch filter to remove the 60Hz power line noise, a buffer, and a low-pass filter (LPF). For the notch filter, we use a Twin-T notch filter with a 60Hz cut-off frequency [24], and the buffer, whose gain is 1 [V/V], is connected to the output of the notch filter to improve the stability of the filtered ECG signals. For the LPF, we use a second active low-pass filter with a 35Hz cut-off frequency.

IV. PERFORMANCE DEMONSTRATION OF THE PROPOSED SYSTEM

In this section, we demonstrate the performance of the proposed system installed in a test vehicle and analyze the performance results in detail. We use a Nissan Cube as the test vehicle, and we install the proposed signal-conditioning circuit inside of the driver air bag (DAB) cover of the steering wheel. We use CHC's CHC B20 [25] as the differential global-positioning system (DGPS) navigation equipment, which has maximum positioning accuracy of 0.75m, to log the driving experiment trajectory.

A. MEASURING THE PERFORMANCE WHEN IDLING

We analyze the ECG measuring performance of the proposed system in idling and driving conditions using the R-peak detection rate D (1), an index which measures the signal-detection performance, and the R-peak attenuation rate A (2), an index which measures signal attenuation in the driving environment. These are defined, respectively, as

$$D = \frac{N_r}{N_R} \times 100[\%] \tag{1}$$

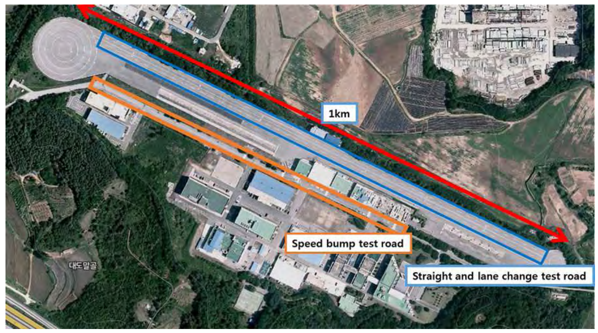


FIGURE 8. Test environment at Korea Automotive Technology Institute in South Korea [26].

$$A = \frac{\sum_{i=1}^{N_r} v_i}{V_{MAX} N_r} \times 100[\%], \tag{2}$$

where N_R is the total number of R-peaks which occur during N seconds, N_r is the number of R-peaks that have effective peaks over the threshold value during N seconds, V_{MAX}(=3[v]) is the maximum value of the R-peak amplitude present in the ECG signals measured in N seconds, and v_i is the i-th instance of R-peak amplitude.

For reliable detection of the R-peaks, we propose a histogram-based threshold determination technique. To create the ECG signal histogram, we collect ECG signal samples for N seconds (N=60) as shown in Fig. 9(a). P-waves, PR-segments, ST-segments, and T waves are widely spread with similar amplitudes in each cycle of the ECG signals, as shown in Fig. 9(b). We find a concentrated region in the histogram of the ECG signal samples, as depicted in Fig. 9(d), which corresponds to the P-waves, PR-segments, ST-segments, and T waves that appear the most in the collected samples. This allows us to the threshold value by adding a margin for consideration of false alarms. Fig. 9(c) shows the ECG signal over two cycles to illustrate the histogram-based threshold determination technique. Note that the ECG signals in orange and purple in Fig. 9(c) correspond to the histogram within the orange box and the purple box in Fig. 9(d), respectively. As shown in Fig. 9(c), we establish the threshold value by applying a margin above the orange signal level.

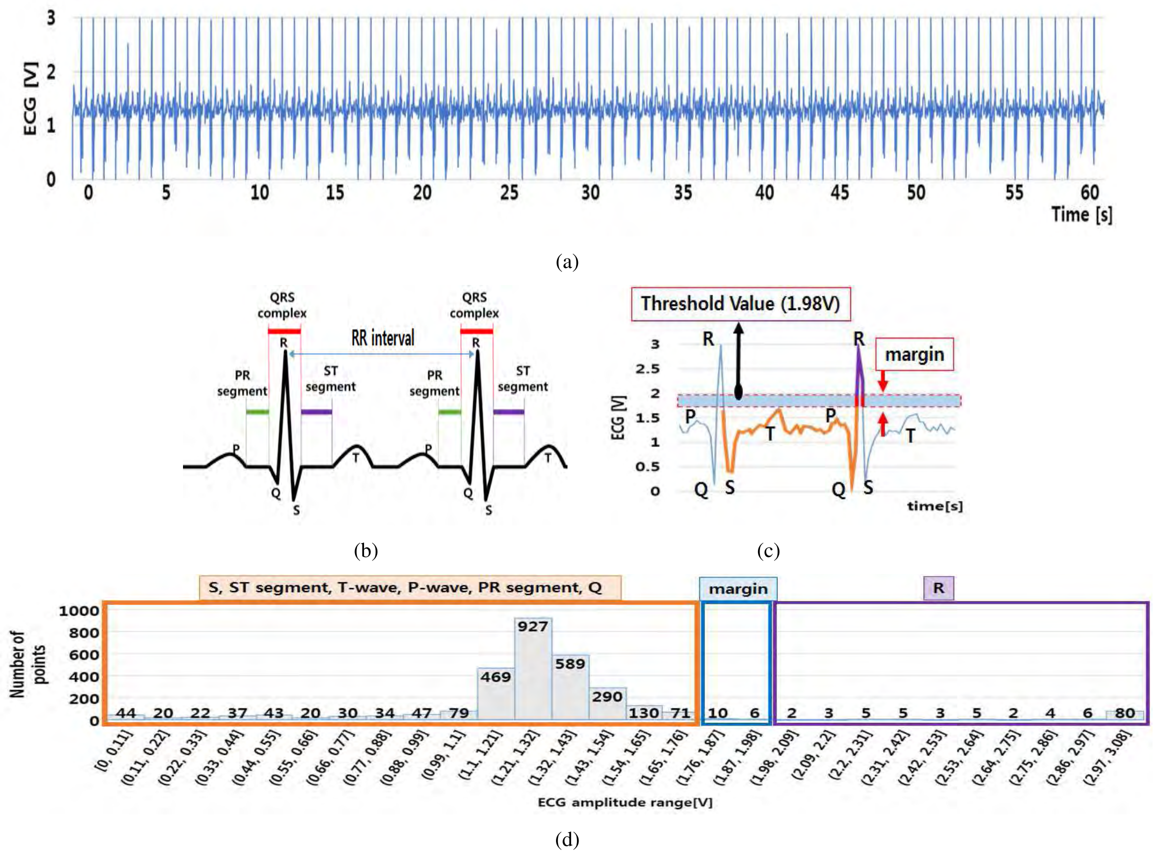


FIGURE 9. **Histogram-based threshold determination technique. (a) ECG data measured for 60 seconds in an idling condition. (b) Ideal ECG signal waveform. (c) ECG signal over two cycles to determine the detection threshold. (d) Histogram of the ECG signal measurements.**

We demonstrate the performance of the proposed system in an idling state using the R-peak detection rate D (1) and R-peak attenuation rate A (2). As shown in Fig. 9(a), the rates of D and A calculated with ECG signals measured for 60 seconds in the idling state are 100% and 99.22%, respectively. This result provides evidence that the proposed ECG measuring system is capable of accurate and reliable ECG measuring performance when the vehicle is idling.

To demonstrate the reliability of the proposed system, we compare the ECG signals measured by the proposed system for 60 seconds, as shown in Fig. 10(a) to the ECG signals measured with a clinical ECG measuring system (BM5 [27]) for 60 seconds, as illustrated in Fig. 10(b). Because the two systems use different signal-conditioning circuits, we compare only the D rates of the ECG signals from the two systems. As shown in Fig. 10(c) and Fig. 10(d), the numbers of R-peaks measured from the two systems are 70 (with the BM5) and 69 (with the proposed system), with a D rate of 100% for both systems. This indicates that the numbers of R-peak and the D rates of the ECG signals are nearly identical for both systems, confirming that the proposed system for use in a vehicle environment is capable of performance equivalent to that of a clinical ECG measuring system in a stable environment.

B. MEASURING PERFORMANCE DURING DRIVING

To demonstrate the ECG measuring performance of the proposed system in a driving environment, we use the proving ground track at the Korea Automotive Technology Institute (KATECH), which has a 1km straight lane test road, a changing lane test road, and a speed bump test road, as shown in Fig. 8.

In the driving test, as shown in Figs. 11(a), 12(a), and 13(a), the test vehicle drives on the proving ground track at a maximum speed of 80km/h and the driver grips the steering wheel stably with both hands. We calculate D (1) and A (2) from the measured ECG signals and obtain the following values: $D = 95.31\%$ and $A = 87.68\%$ for straight driving, $D = 90.80\%$ and $A = 85.72\%$ for driving over the speed bumps, and $D = 92.94\%$ and $A = 85.50\%$ for driving with lane changes. These results show that A is reduced by 11.54% for straight lane driving, by 13.5% when driving over the bumps, and by 13.72% for driving with lane changes compared to the test result in the idling state. It was also found that unstable contact between the steering wheel and the driver's hands on the steering wheel results in instantaneous degradations of A, as observed with the ECG signals within the five yellow boxes shown in Fig. 12(b). However, although A is reduced during the driving state, D still shows an average

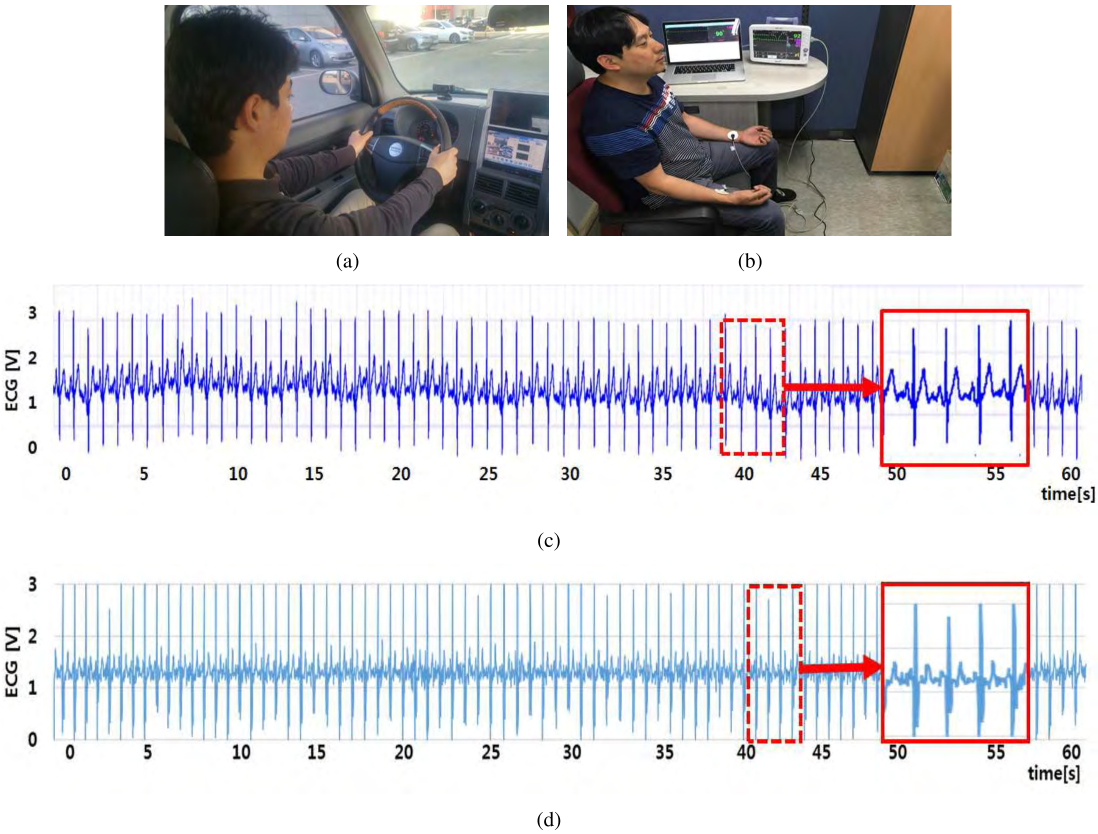


FIGURE 10. Comparison of ECG measurements with the proposed ECG measuring system and BM5. (a) measuring ECG signals with the proposed system. (b) Measuring ECG signals with BM5. (c) Measured ECG signals with BM5. (d) Measured ECG signals with the proposed system.

rate of 93.01% in all three driving conditions. This result shows that the proposed system is capable of reliable R-peak detection performance in various driving environments.

C. ANALYSIS OF SENSOR STABILITY

When the vehicle drives over speed bumps or changes lanes, unstable contact may occur between the driver's hands on the steering wheel and the dry electrode on the steering wheel. In this case, it may be difficult to measure ECG signals from the proposed system stably until the contact between the driver's hands and the dry electrode on the steering wheel is stabilized. Therefore, it is important to demonstrate the signal detection recovery performance of the proposed ECG measuring system in the event of unstable conditions.

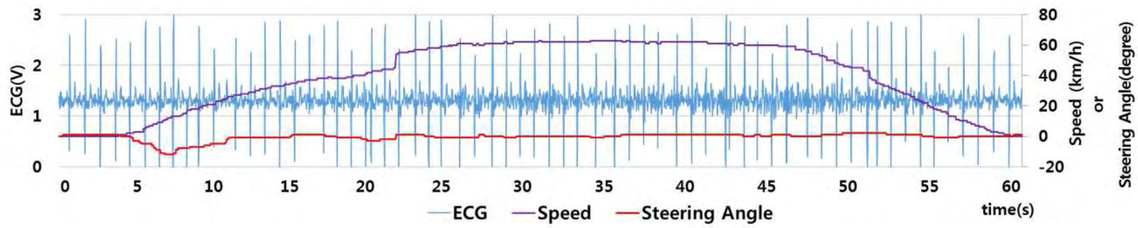
Fig. 14 depicts the ECG signal detection recovery performance using the threshold proposed in Fig. 9. Fig. 14(a) shows the driving trajectory over the first four speed bumps shown in Fig. 12(a). The test vehicle drives over the four speed bumps at a maximum speed of 30km/h. As shown in Figs. 14(b)-14(e), the proposed system recovers its normal state within a maximum of two ECG cycles after passing over the four speed bumps. This result shows that the proposed system offers very fast ECG signal detection recovery performance after disturbances by speed bumps.

D. ANALYSIS OF THE ECG MEASURING PERFORMANCE FOR DROWSY DRIVING

Because the ECG signal measurements are tightly correlated with the driver's cardiac activity, the cycle of the ECG signals changes according to the driver's condition, such as drowsiness and/or fatigue [20]. This subsection describes the performance of the proposed ECG measuring system related to drowsy drivers by comparing ECG signals measured in a normal driving condition and those measured in a drowsy driving condition.

In the experiments, we measure and compute the driver's ECG signals in an idling state when the driver is in a normal condition and in a drowsy condition. Fig. 15 shows ECG signals measured for 60 seconds when a driver is in a normal condition (blue plot) and when the same driver is in a drowsy condition (green plot). As shown, the numbers of R-peaks in the normal and drowsy conditions are 66 and 58, respectively, demonstrating that the number of R-peaks in the drowsy condition is decreased by 12.12% compared to that in the normal condition. In addition, the D rates in the normal and drowsy conditions are 98.48% and 94.82%, respectively. This result indicates that the proposed system not only shows reliable detection performance for drowsy driving as long as the driver grips the steering wheel properly with both hands,

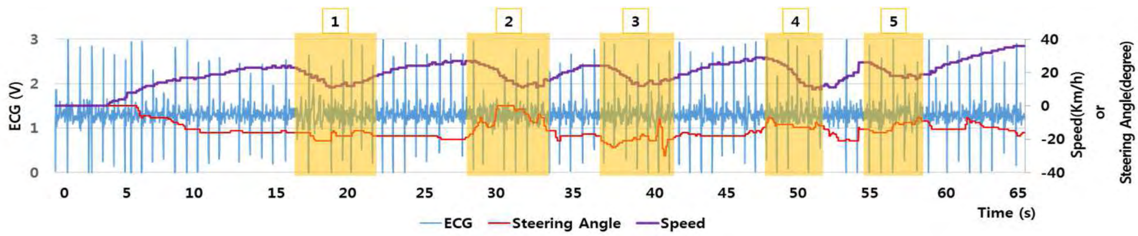
(a)



(b)

FIGURE 11. Test result for straight lane driving. (a) Test driving trajectory. (b) Test results.

(a)



(b)

FIGURE 12. Test result for driving over speed bumps. (a) Test driving trajectory. (b) Test results.

but that it also demonstrates good applicability for driver status monitoring.

E. SNR COMPARISON WITH THE MEASURED ECG SIGNAL

To compare the ECG signal-measuring performance of the proposed system with that of existing systems [7], [8], we calculate the SNR (signal-to-noise ratio) of the measured ECG signals for straight driving, driving over speed bumps, and driving with lane changes [28]–[31]. Because the R-peak within the QRS complex is classified as a major component in DSM algorithms, it should be clearly distinguished from other ECG signal components, such as the P-wave and T-wave, in the isoelectric region, as noted above [29]. The SNR of ECG signals, as the ratio of the R-peak to the noise power in the isoelectric region, is defined as

$$\mathrm{SNR} = 20\log_{10}\left(\frac{\mathrm{S}_{\mathrm{amp}}}{\mathrm{N}_{\mathrm{amp}}}\right)\Bigg|_{\text{isoelectric region}}, \tag{3}$$

where $\mathrm{S}_{\mathrm{amp}}$ is the R-peak amplitude and $\mathrm{N}_{\mathrm{amp}}$ is the noise amplitude in the isoelectric region. Because the ECG measuring systems proposed by BMW [5], [6] and Daimler AG [11] do not discuss the SNR of the measurements, we only compare the SNR measured with the proposed system to that measured with the Denso ECG measuring system [7], [8].

Table 1 shows the results of the comparison of the SNR of the ECG signals measured by the proposed system and measured by the Denso system in the idling and driving states [7]. In their study [7], Denso recommends a SNR

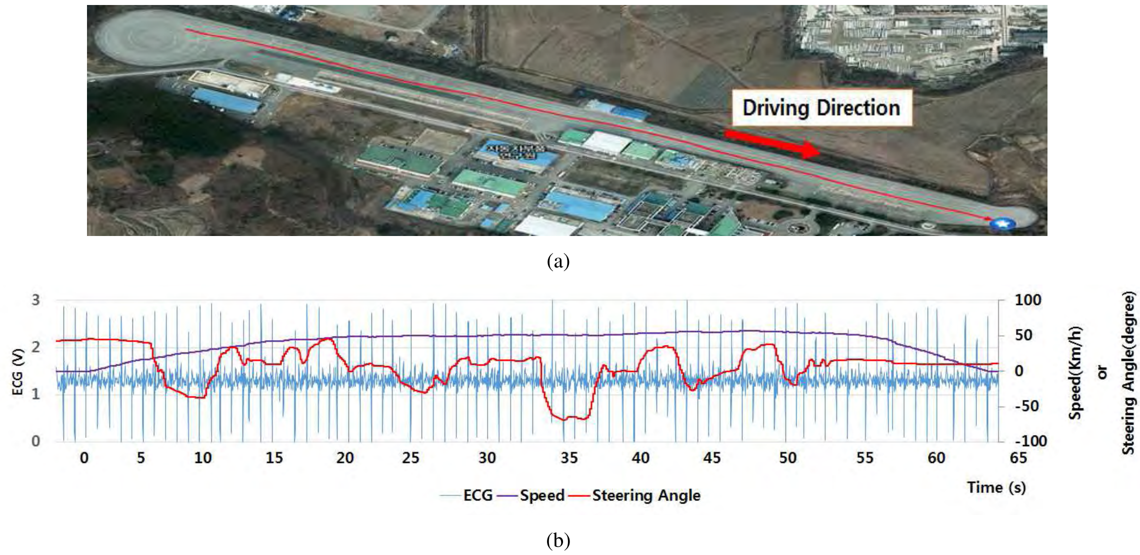


FIGURE 13. Test result for driving with lane changes. (a) Test driving trajectory. (b) Test results.

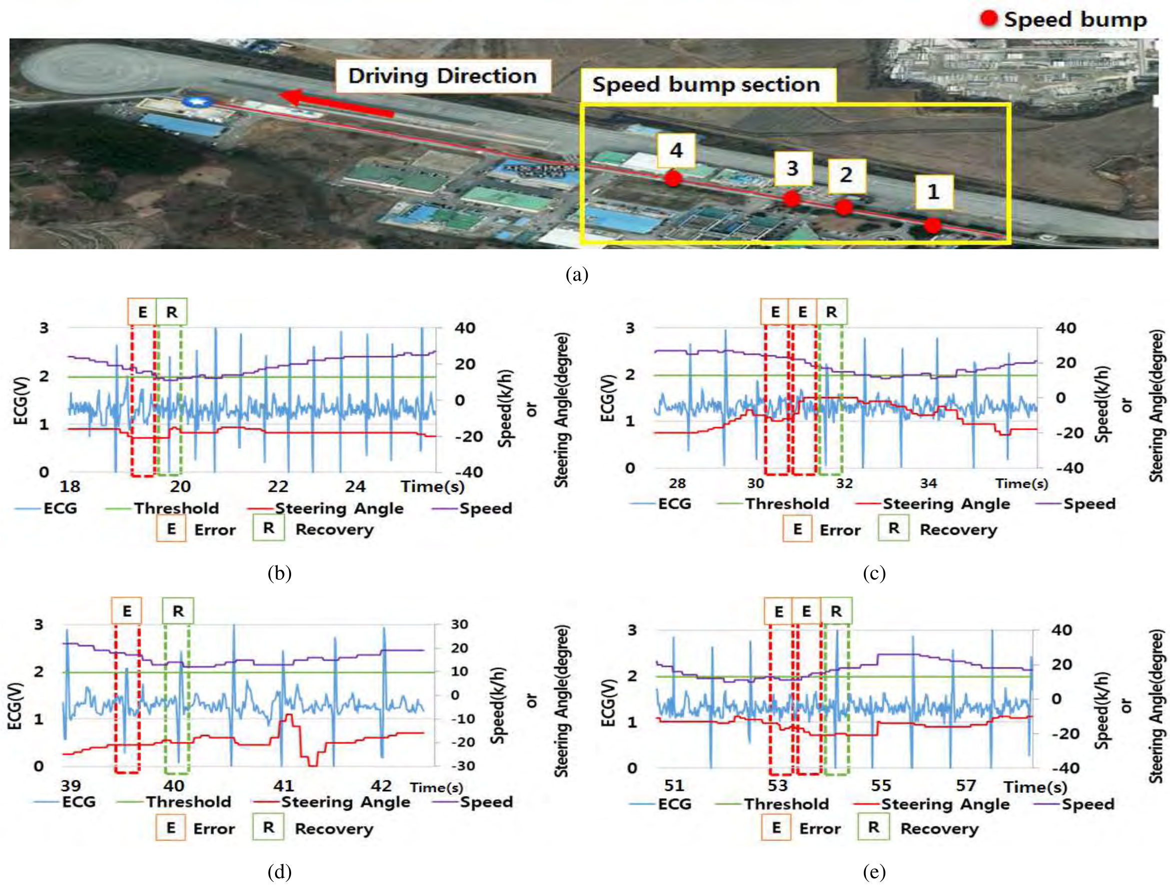


FIGURE 14. Test results of ECG signal detection recovery from driving over speed bumps. (a) Test trajectory with four speed bump locations. (b) Test results for the speed bump 1. (c) Test results for the speed bump 2. (d) Test results for the speed bump 3. (e) Test results for the speed bump 4.

of 10dB as the minimum requirement for valid ECG signal measurements in the driving state. As shown in Table 1, the SNRs of the ECG signals measured by the proposed system are 15.11dB in the idling state and 12.69dB in the driving state, thus meeting the minimum requirement of the SNR recommended by Denso [7]. Table 2 shows the results

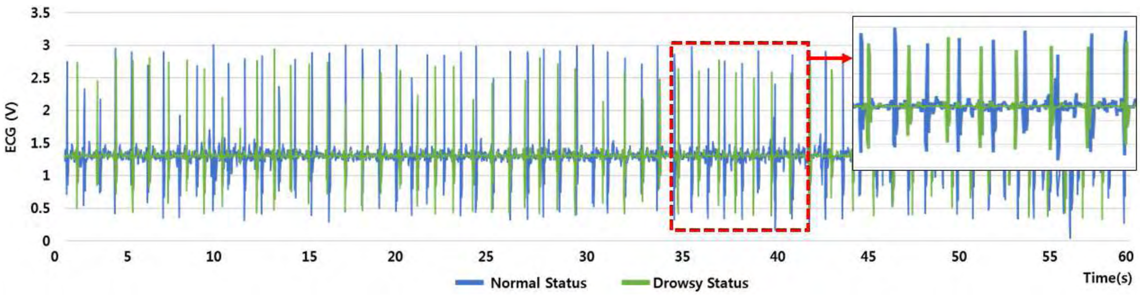


FIGURE 15. Comparison of measured ECG signals for 60 seconds in a normal condition and a drowsy condition.

TABLE 1. SNR comparison of measured ecg signals in idling and driving states.

Test condition		SNR [dB]	
Speed [km/h]	Driving condition	Denso [7] (contact and noncontact-based ECG measuring system)	Proposed system (contact-based ECG measuring system)
0	idling state	8.7	15.11
80	curve and straight driving	6.4	-
	curve driving	-	12.69
	changing lane driving	-	11.22

TABLE 2. SNR difference comparison of measured ECG signals in idling and driving states.

Experimental condition	SNR [dB]		
	Denso [7] Suggested system	Denso [8] (contact and noncontact-based ECG measuring system)	Proposed system (contact-based ECG measuring system)
Difference between idling and straight driving [7] (or with curve driving [8] with curve driving and straight driving	8	2.3	2.42

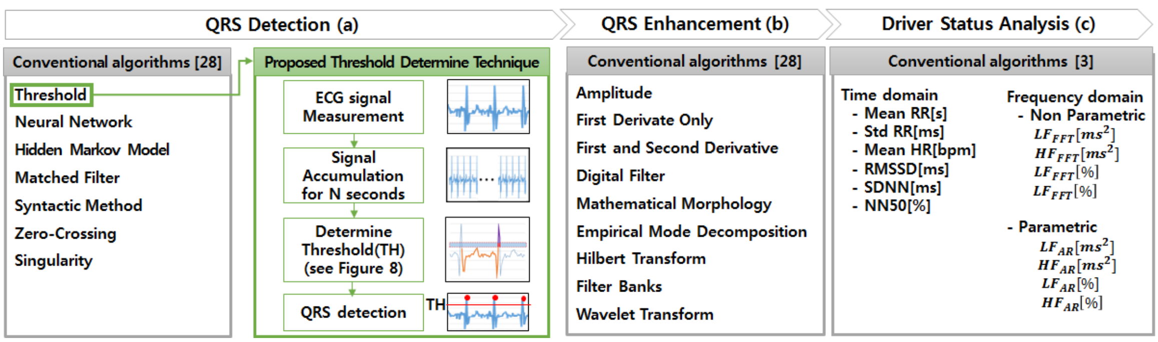


FIGURE 16. Application of the proposed threshold determination technique to conventional DSM algorithms [3], [32].

of a comparison of SNR difference in the idling state and driving state [7], [8]. As shown in Table 2, the SNR difference in the measured ECG signals between the idling state and straight driving is only 2.42dB with the proposed system, which is 5.58dB less than the value of 9dB with the Denso ECG measuring system [7], which testifies the significant performance improvement achieved by the proposed system. Table 2 also shows that the SNR difference with the proposed system (SNR=2.42dB) is similar to that by the Denso (contact and noncontact-based combined) ECG measuring system (SNR=2.3dB) [8]. The results in Table 2 demonstrate that the proposed system measures ECG signals more reliably than Denso's system [7]. Moreover, simultaneously it shows very similar ECG measuring performance to that of a contact and noncontact-based ECG measuring system [8].

The proposed dry electrode utilizing the electroplating method and the employed conductive fabric-shaping procedure together produce smooth and uniform contact between the dry electrode wrapped around the steering wheel and the driver's hands as they grip the dry electrode, resulting in enhanced ECG signal detection stability. As a result, the proposed ECG measuring system shows better SNR performance than the circuits in Denso's ECG measuring system, despite its use of only a basic signal-conditioning circuit that is simpler than Denso's ECG measuring systems [7], [8]. Because the aforementioned advantages of the proposed system stem from the proposed dry electrode, it is necessary to describe the development procedure of the dry electrode. This is done in Section II in detail.

F. DISCUSSION FOR REAL-TIME IMPLEMENTATION

In general, a DSM algorithm detects ECG signals and enhances the detected ECG signals to analyze the driver's condition. As shown in Fig. 16, conventional DSM algorithms are divided into the QRS detection block, QRS enhancement block, and driver status analysis block. There are various algorithms for each block. The proposed histogram-based threshold determination technique, which allows only a very small number of false alarms, can be applied to the threshold-based QRS detection algorithm in the conventional QRS detection block, as shown in Fig. 16(a). After doing so, QRS enhancement algorithm enhances the detected QRS complex, as shown in Fig. 16(a). The QRS enhancement algorithm then enhances the detected QRS complex as shown in Fig. 16(b). Finally, the driver status analysis block uses the improved QRS complex to analyze the driver's status, as shown in Fig. 16(c).

V. CONCLUSION

In this paper, we proposed a conductive fabric-based dry electrode (dry electrode, in short) utilizing an electroplating method and employed a conductive fabric-shaping procedure. We used the proposed dry electrode as a steering wheel cover in order to measure the ECG signals of a driver. Furthermore, we developed an ECG measuring system using the proposed dry electrode and a basic signal-conditioning circuit. Through tests under various road conditions and vehicle environments, it was found that the proposed ECG measuring system offers accurate, stable, and reliable performance in comparison to the capabilities of conventional ECG measuring systems. In addition, by comparing the measured ECG signals of a driver in a normal condition to those in a drowsy condition, we showed that the proposed ECG measuring system is useful for detecting drowsy drivers.

In future work, we plan to develop a robust and reliable DSM algorithm based on artificial intelligence such as deep learning using ECG signals obtained from the developed steering wheel during driving.

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