

Design and Implementation of a Data-Driven Defect and Linearity Assessment Monitoring System for Electric Power Steering

Lawal Alabe Wale¹, Kimleang Kea¹, Youngsun Han^{2*}, Tea-Kyung Kim³

¹Student, Dept. of AI Convergence, Pukyong National University

²Professor, Dept. of AI Convergence, Pukyong National University

³Professor, Dept. of Marketing Bigdata, Incheon JaeNeung University

전동식 파워 스티어링을 위한 데이터 기반 결함 및 선형성 평가 모니터링 시스템의 설계 구현

알레 알라비 라왈¹, 키에 킴링¹, 한영선^{2*}, 김태경³

¹부경대학교 인공지능융합학과 대학원생, ²부경대학교 인공지능융합학과 교수, ³인천재능대학교 마케팅빅데이터과 교수

Abstract In recent years, due to heightened environmental awareness, Electric Power Steering (EPS) has been increasingly adopted as the steering control unit in manufactured vehicles. This has had numerous benefits, such as improved steering power, elimination of hydraulic hose leaks and reduced fuel consumption. However, for EPS systems to respond to actions, sensors must be employed; this means that the consistency of the sensor's linear variation is integral to the stability of the steering response. To ensure quality control, a reliable method for detecting defects and assessing linearity is required to assess the sensitivity of the EPS sensor to changes in the internal design characters. This paper proposes a data-driven defect and linearity assessment monitoring system, which can be used to analyze EPS component defects and linearity based on vehicle speed interval division. The approach is validated experimentally using data collected from an EPS test jig and is further enhanced by the inclusion of a Graphical User Interface (GUI). Based on the design, the developed system effectively performs defect detection with an accuracy of 0.99 percent and obtains a linearity assessment score at varying vehicle speeds.

Key Words : Defect detection, Electric power steering (EPS), Electronic control unit, Linearity assessment, sensor

요약 최근에는 환경에 대한 인식이 높아지면서 제조 차량에서 전자식 파워 스티어링(EPS)이 조향장치로 채택되는 사례가 증가하고 있다. EPS는 스티어링 파워 향상, 유압 호스 누출 제거 및 연료 소비 감소와 같은 수많은 이점을 제공하지만, 시스템이 움직임에 반응하게 만드는 센서를 요구한다. 이는, 센서의 선형 변동성을 유지하는 것이 스티어링 반응의 안정성에 필수적임을 의미한다. 따라서 EPS의 제어 품질을 보장하기 위해 내부 설계 특성의 변화에 대한 센서의 민감도, 결함 및 선형성을 평가하기 위한 신뢰성 있는 방법이 필요하다. 본 논문은 차량속도 구간 분할을 기반으로 EPS 구성요소 결함과 선형성을 분석하는 데이터 중심 결함 및 선형성 평가 모니터링 시스템을 제안한다. EPS 테스트 지그에서 수집된 데이터를 사용하여 모니터링 시스템의 성능을 검증하였으며, 그래픽 사용자 인터페이스(GUI)를 적용하여 시스템을 개선하였다. 개발된 시스템은 설계를 기반으로 0.99% 정확도의 결함 감지 및 가변적인 차량속도에서 선형성 평가를 효과적으로 수행하였다.

주제어 : 결함 감지, 전자식 파워 스티어링, 전자식 제어 장치, 선형 측정, 센서

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*교신저자 : 한영선(youngsun@pknu.ac.kr)

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1. INTRODUCTION

Early steering systems were either heavily or lightly geared. To address these issues, a power-assisted steering system was created. Compared to hydraulic power steering, EPS brought significant enhancements to vehicle control systems. It reduces the power needed to turn the steering wheel, eliminates hydraulic hoses, conserves fuel consumption, and reduces the risk to vehicle intrusion through the use of Internet of Thing (IoT)[1-6].

For EPS to be effective, there must be an interactive connection between various mechanical and electrical components, such as an angle sensor, torque sensor, vehicle speed sensor, and electric motor. The electric motor intensifies the assistance torque, decreasing the torque the driver must use to turn the wheels. The Electronic Control Unit (ECU) determines the amount of power supplied based on a motor assist table which includes an assistance rule based on vehicle speed and torque sensor readings [7]. EPS system relies on sensors to generate responses to the driver's actions. Consequently, the stability of the EPS response is dependent on the accuracy of the sensor linear variation.

The rising demand for EPS systems due to the increased popularity of hybrid and self-driving vehicles requires the need to improve defect and linearity assessment of the EPS system to eliminate sub-standard components. Previous studies have focused on fault diagnosis, tolerance, and control of the EPS system using a model and knowledge-based approach [8,9]. In [10], optimization of the EPS front steering angle control is discussed using pole placement and linear quadratic controller to provide a solution for the nonlinear behavior caused by variable gear ratios and friction. The performance of the proposed controller design was verified using its trajectory following abilities for both linear and nonlinear systems. To address the issue of torque

damping in EPS caused by motor and mechanical friction, mechanical and electrical friction compensators were utilized in [11]. Theoretical analysis and simulation results have demonstrated that a double closed-loop steering wheel control structure can keep the steering wheel torque close to the desired value, even when mechanical friction torques vary. In [12], an innovative control strategy was proposed for optimizing EPS control to account for modeling errors and parameter uncertainties. This approach was designed to ensure the system responds rapidly to the driver's actions, maintains stability, and provides road feedback to the driver. The control system has been designed using a reference model of a dynamic electric power assist steering system. Simulation results indicate that the control strategy increases the robustness of the EPS and reduces the design time.

The torque sensor is the most important sensor component in an EPS system, as it is essential for providing the driver with the necessary assistance. Therefore, a malfunction of this sensor often leads to a lack of support. In [13], a controller design for EPS was proposed to reduce the number of sensor elements needed and, specifically, to function without torque sensors. The author established a strategy that uses either a controller with driver torque estimation or a controller that doesn't require driver torque.

Research on the development of an EPS evaluation system has been conducted. For example, in [5], an endurance test machine was developed to assess the rustproof and sealing properties of an EPS to prevent water from damaging the motor and ECU. A simulation platform was developed in [14] to determine if the EPS worked according to its design principles, with the aim of reducing economic costs and speeding up the development cycle. In [15], a functional safety compliance ECU was proposed for the EPS, which included an asymmetric dual processing

unit and an external watchdog to check the supply voltage and execution time of the processing unit. The monitoring functions for safety, such as task monitor and redundant, were verified through an EPS test jig.

To ensure the reliable and high-performance of an EPS system, an evaluation mechanism and improved measurement accuracy must be implemented.

In [16], the performance evaluation of an interior permanent magnet (IPM) motor in an EPS was conducted. IPMs offer several advantages in an EPS, such as reducing its size and weight, and providing high torque density with the ability to operate in flux-weakening regions. The effect of steering system linearity was examined in [17] on truck steering systems with linear and nonlinear characteristics. The study used driving simulations conducted by an experienced truck driver and a university student, which exhibit viable vehicle control and a realistic visual experience on the road. Findings demonstrate that the linear steering system requires less perpetual and objective steering effort and efficient lane-keeping accuracy than the nonlinear system. Experienced truck drivers may have a familiarity bias when it comes to novel concepts, since they are used to their existing manual steering system.

To evaluate the functional safety assessment of the internal design characteristic in the EPS, an active linearity assessment platform is necessary, to improve design quality and reliability.

Human activity has been revolutionized by the advent of "Industry 4.0", which is transforming the socioeconomic and manufacturing sectors through IoT sensor devices that generate massive datasets. These datasets have been widely adopted to improve standard of living and decision-making in the areas of intrusion detection [6], smart system [18], defect detection [19], and improving operational efficiency. Advancement in vehicular systems with the usage of IoT has offered a lot of comfort to motorists

and commuters, especially video delivery content. Hence, the cost of internet data communication has an adverse influence on the usage of this service. In [20], a cost-reducing data transmission technique for vehicles-in-motion is proposed through subjective data chunks in the WIFI and mobile communication areas.

This paper proposes a data-driven platform for assessing defects and linearity in EPS based on assembled system components. The use of a data-driven approach is preferred to a modeling-based approach, as it is capable of detecting both minimal and degrading conditions of a system. The major contributions of this work are outlined below:

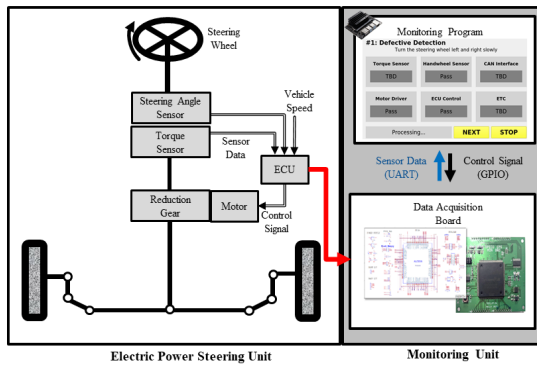
- We propose a data-driven method to enhance the quality control of assembled system components in EPS, as opposed to the typical existing modeling-based approaches that use the residual signal for defect detection.
- We implemented a linear assessment system to evaluate EPS linearity performance, as well as to detect defects.
- To validate our proposed approach, we used the dataset generated experimentally from an EPS test jig.

This paper is organized as follows: Section 2 presents the proposed architecture and implementation details. Section 3 introduces the EPS experimental setup and performance evaluation. Finally, Section 4 provides a summary of the paper.

2. DESIGN AND ARCHITECTURE

In this section, we present the architecture and design of the proposed assessment system. [Fig. 1] displays the framework of our

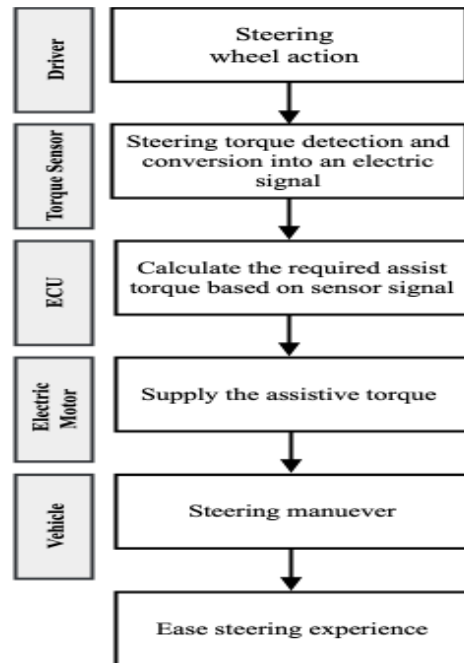
proposed system for evaluating EPS linearity and detecting defects. It comprises of two primary components: an experimental setup of EPS and the assessment monitoring unit.



[Fig. 1] Organization of proposed architecture

2.1 Working Principle of EPS

Numerous types of EPS systems have been proposed, but they all function on a similar concept. As shown in [Fig. 1], the driver manually applies torque to the steering wheel. The torque sensor detects this input and transmits it as an electrical signal to the ECU. The ECU then compares the sensor signal with the steering assist force, considering both internal and external system factors such as vehicle speed and steering angle, and provides steering assist torque accordingly. The reduction gear connected to the steering column amplified the steering torque received from the electric motor. This torque, which is intended to help with steering, is transferred to the pinion gear connected to the steering rack. This converts the rotational motion coming from the steering wheel into lateral motion. As a result, the force generated by the rack is transmitted through the tie rod to push the knuckle arm, causing the tires to turn at an angle. [Fig. 2] shows the workflow of an EPS system.



[Fig. 2] Workflow of EPS

2.2 Monitoring Unit

In accordance with the operational procedure of the EPS system, the data acquisition board receives the driver steering angle, torque, and speed signals from the EPS via the ECU unit. The data received from the ECU is used to conduct defect detection, following the flow presented in [Fig. 3]. By comparing the defect parameters of torque sensors, handwheel sensors, motor drivers, and ECUs, the system initiates the process of detecting faults. Furthermore, it determines steering effort, lag, and reaction tests at different vehicle speeds by measuring steering torque and the angle of the steering wheel.

Steering effort is a critical parameter of the EPS system, which estimates the force required to rotate the steering wheel. The catch-up feature illustrates how the steering system adapts and synchronizes with the driver's input, enabling the vehicle to respond more rapidly and accurately. The response of the steering system measures its speed in reacting to changes in

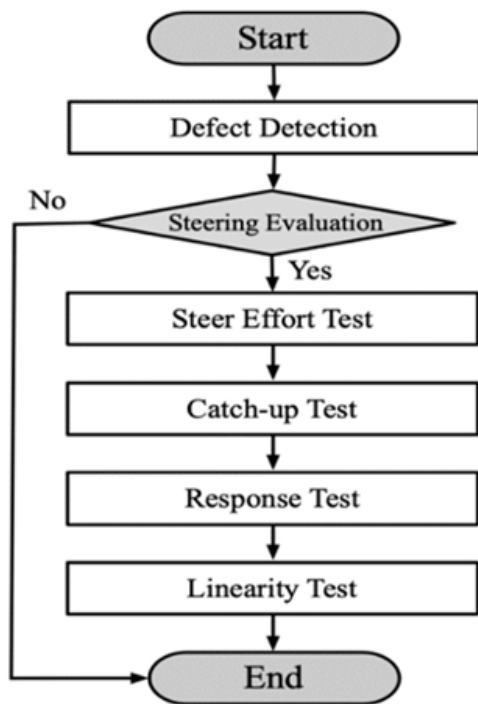
driver input, while its linearity assesses the consistency of its adjustments to these driver actions. A linear response signifies a proportional alignment with the driver's input, while a nonlinear response may lead to an unexpected or inconsistent steering reaction. The method for calculating the steering evaluation is detailed in Algorithm 1.

The algorithmic procedure for evaluating steering begins with sensor data pre-processing. This pre-processing step is essential, as it lays the groundwork for accurate and reliable steering evaluation. By removing abnormal data, interpolating "NaNs", and clipping the signal, the data used for evaluation becomes more representative of the actual measurements, thus eliminating inaccuracies in the analysis. Following this, the steering evaluation process commences with the selection of output parameters, starting with the steering effort and continuing with the previously mentioned parameters.

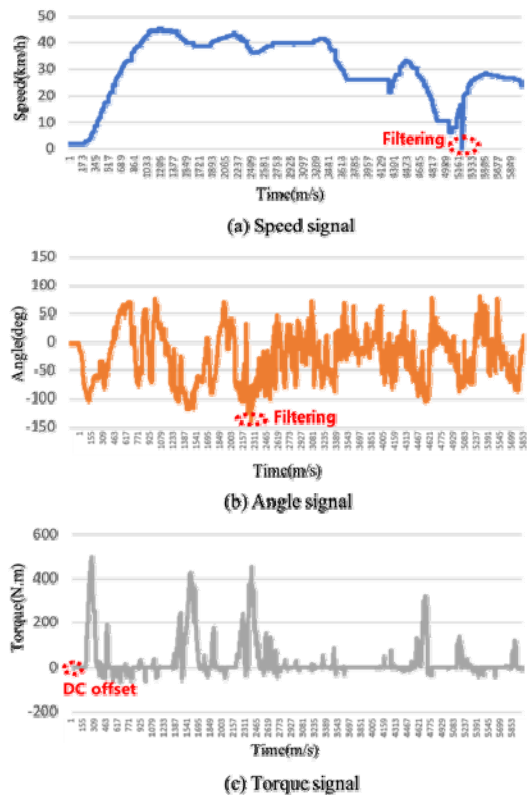
Algorithm 1 Steering Evaluation

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INPUT  $\{X_{a,t}\}$ : set of EPS sensor data.  $a$ : angle,  $t$ : torque
OUTPUT steer effort, catch_up, response, linearity
1: procedure STEERING_EVALUATION( $X_{a,t}$ )
2:   // pre-processing of input data
3:   P = pre_processing( $X_{a,t}$ )
4:   // selection of evaluation parameter
5:   mode  $\leftarrow$  selection of output parameter
6:   if mode == 0 then
7:     steer_effort = calculate_steer_effort(P)
8:   else if mode == 1 then
9:     catch_up = calculate_catch_up(P)
10:  else if mode == 2 then
11:    response = calculate_response(P)
12:  else if mode == 3 then
13:    linearity = calculate_linearity(P)
14:  end if
15: end procedure
    
```



[Fig. 3] Execution flow of EPS defect detection



[Fig. 4] Signal pre_processing

The graphical interface of the linearity assessment includes the option to load a vehicle, sensor signals in the time domain for data mining

debugging and system operation checks, and linearity points according to the speed interval. The pseudocode for determining the linearity point is provided in Algorithm 2. The linearity assessment, as described in the algorithm, starts with a similar procedure to steering evaluation, which includes data pre-processing to remove spiking noise and DC offset signals. A threshold is established based on the angle signal to eliminate invalid sensor data. Figure 4 illustrates the signal pre-processing stage.

The linearity point is calculated by taking the sum of the torque signal divided by the angle signal, followed by a linear regression equation to obtain all the linearity points as defined in equation (1).

$$y_{predict} = b_1x + b_0 \quad (1)$$

where $y_{predict}$ is the predicted point, x is the reference sample, b_1 is the linearity obtained from the sample covariance divided by the sample variance, and b_0 is the intercept.

Algorithm 2 Linearity Assessment

INPUT $\{X_{s,a,t}\}$: set of EPS sensor data. s : speed, a : angle, t : torque

OUTPUT $\{X_{i,lps}\}$: list of interval and linearity point

```

1: procedure LINEARITY_ASSESSMENT( $X_{s,a,t}$ )
2:   // pre-processing of input data
3:    $P_{s,a,t} = \text{pre\_processing}(X_{s,a,t})$ 
4:   // threshold of valid angle signal
5:    $thv \leftarrow$  threshold of valid angle signal
6:   // validate angle value
7:    $thv\_flag = P_a \leq thv$ 
8:   // calculate linearity point
9:   for  $i \in (0, \text{len}(thv\_flag))$  do
10:    if  $thv\_flag[i]$  then
11:      interval += 1
12:       $lps = \frac{\sum P_a}{\sum P_t}$ 
13:      append interval and lps to  $X_{i,lps}$ 
14:    end if
15:  end for
16: end procedure

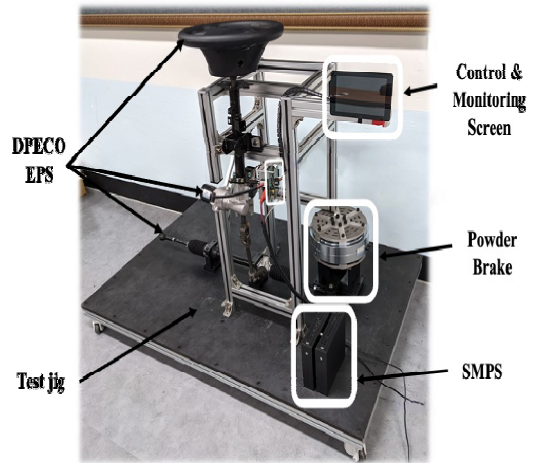
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3. EXPERIMENTAL SETUP AND EVALUATION

In this section, we present the experimental setup and evaluation result.

3.1 Experimental Setup

A test jig of an EPS, as illustrated in [Fig. 5], was adopted to experimentally verify the performance of the EPS defect and linearity assessment monitoring system. The test jig featured a steering column connected to the rack. The running speed ranged from 0-60km/h, and the data acquisition board employed was a field-programmable gate array (FPGA) connected to the ECU.



[Fig. 5] Setup of EPS test environment

The ECU transfer sensor data is used to conduct defect detection of the monitoring system through comparison. In the case of a defect component, the default obtained sensor data parameter changes as depicted in <Table 1> and <Table 2> present sample EPS data format.

<Table 1> Defect parameter format

NO	Transfer Value (HEX)	Transfer Data (ASCII)	Packet	Description
1	Fault Diagnosis			
	40'h30303030300D	00000^M	10	- Normal
	40'h30313031300D	01010^M	10	- HS: Error - MD: Error

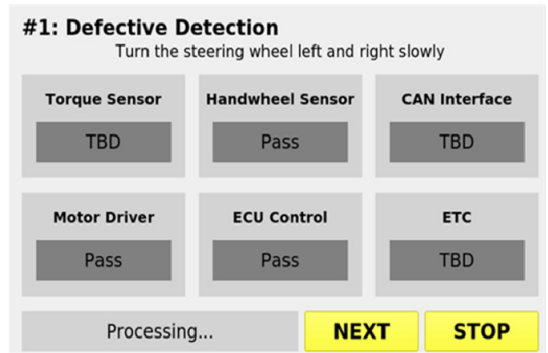
No	Parameters	Transfer Data (ASCII)	Error Detect
1	Torque Sensor (TS)	0	Pass
2	Handwheel Sensor (HS)	1	Fail
3	CAN (CN)	0	Pass
4	Motor Driver (MD)	1	Fail
5	ECU (EC)	0	Pass

<Table 2> EPS sensor format

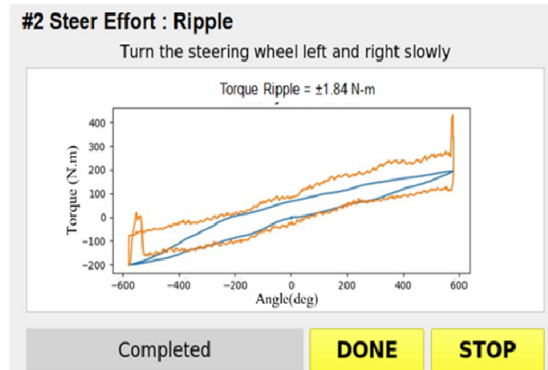
NO	Transfer Data (ASCII)	Transfer Value (HEX)	Description
1.	Handwheel Angle		
	ANG: +0720^M	40'h414E473A2 B303732300D	Handwheel angle = +720°
	ANG: -1003^M	40'h414E473A2 D313030330D	Handwheel angle = - 1003°
2.	Steering Torque		
	TRQ: +13.2^M	40'h5452513A2 B31332E20D	Steering torque = +13.2Nm
	TRQ: -05.9^M	40'h5452513A2 D30352E39D	Steering torque = -5.9Nm

3.2 Experimental Result

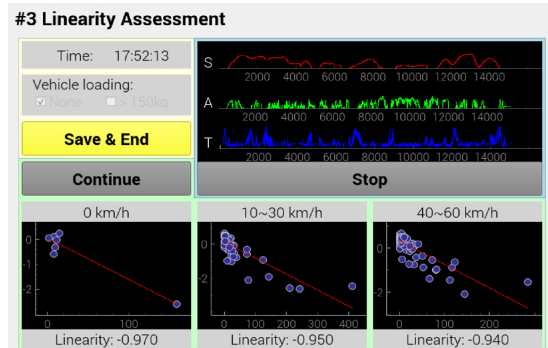
[Fig. 6] shows the monitoring results from an EPS system for defect detection and linearity assessment. The defect detection monitoring program (DDMP) obtains pass/fail status for EPS components by analyzing defect parameters. Steering evaluation is conducted by plotting the transferred data on a graph, with handwheel angle on the X-axis and steering torque on the Y-axis. The linearity of the EPS system is assessed using a pre-defined configuration of 0.95 and a measurement tolerance of ±5%. Linearity is classified according to the speed range from 0 to 60 km/h. A point corresponding to the predicted value is plotted on a graph with the interval on the x-axis and the linearity point on the y-axis



(a). Defect Detection



(b). Steer Effort



(c). Linearity Assessment

[Fig. 6] Example of EPS monitoring result

<Table 3> and <Table 4> display the steering evaluation results for the EPS system installed in DPECO's electric vehicle [21].

〈Table 3〉 Defect detection and steering evaluation

No.	Test Mode	Result
1.	Defect Detection	100%
2.	Steer Effort	1.9N·m
3.	Catch-up	6.2N·m
4.	Linearity	0.94%
5.	Response	0.22 Nm/deg

〈Table 4〉 Linearity assessment result

No.	Speed-Interval (Km/h)	Linearity
1.	0-10	0.97
2.	10-30	0.95
3.	40-60	0.94

4. CONCLUSION

To ensure the reliable and high-performance of an EPS system, an evaluation mechanism and improved measurement accuracy must be implemented. This paper demonstrates the feasibility of an EPS defect and linearity assessment system for enhancing safety design and improving the reliability of EPS systems. Defect and linearity can be tested before mass production, and results can be obtained accurately. The proposed monitoring system is tested based on torque, speed, and angle sensor data received through the ECU of EPS test jigs, to determine EPS defect and linearity at varying speeds. Consequently, we confirm the outcome of our approach showed significant results in assessing the EPS system.

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알레 알라비 라왈(Lawal Alabe Wale) [준회원]



- 2019년 6월 : Kwara State University 전기전자공학과(공학석사)
- 2021년 9월 ~ 현재 : 부경대학교 일반대학원 인공지능융합학과 석사과정

<관심분야>

디지털 회로 디자인, 임베디드 시스템 최적화

키에 킴령(Kimleang Kea) [준회원]

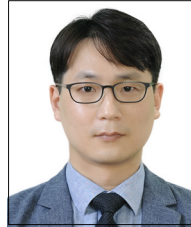


- 2020년 2월 : Royal University of Phnom Penh 컴퓨터공학과(공학석사)
- 2021년 9월 ~ 현재 : 부경대학교 일반대학원 인공지능융합학과 석사 통합과정

<관심분야>

딥러닝, 임베디드 시스템

한 영 선(Youngsun Han) [정회원]



- 2003년 2월 : 고려대학교 전기전자공학부(공학석사)
- 2009년 2월 : 고려대학교 일반대학원 전기전자공학부(공학박사)
- 2009년 6월 ~ 2011년 2월 : 삼성 LSI 사업부 책임연구원

- 2011년 3월 ~ 2019년 8월 : 경일대학교 전기전자공학과 조교수
- 2020년 9월 ~ 현재 : 부경대학교 컴퓨터공학과 부교수

<관심분야>

양자컴퓨팅, 컴파일러 설계, 마이크로아키텍처, 고성능 컴퓨팅

김 태 경(Tea-Kyung Kim) [정회원]



- 2005년 2월 : 충북대학교 정보산업공학(공학석사)
- 2010년 2월 : 충북대학교 정보산업공학과(공학박사)
- 2013년 4월 ~ 2019년 7월 : 한국 소프트웨어 HRD 센터/센터장

- 2020년 3월 ~ 현재 : 인천재능대학교 마케팅빅데이터과 조교수

<관심분야>

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