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Adaptive Door Speed Control for Train Systems under Low-resolution Encoder Constraints

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In train door control systems, the accuracy of door opening and closing time directly affects operational efficiency and passenger safety. However, in legacy rolling stock, limitations imposed by low-resolution encoders and fixed mechanical structures make precise time control challenging. Although the variable-step speed control method proposed in previous studies improves system stability, it is still affected by the rising profile during the startup phase, resulting in a discrepancy between the preset and actual completion times. For example, when the desired door opening time is set to 3.2 s, the measured completion time is often delayed to 3.4–3.5 s, indicating that speed-feedback-based control alone cannot fully compensate for the initial delay. To address this issue, in this paper, we propose a speed command compensation mechanism based on a triangular approximation method. By estimating the time offset introduced by the startup rising interval, the reference speed is automatically adjusted to better match actual system requirements while avoiding overshoot caused by excessive compensation. The proposed method does not necessitate the modification of existing hardware and is compatible with low-resolution encoder feedback, making it practical and cost-effective to implement. The reported improvement rate is evaluated under a fixed load condition with a target operation time of 3.2 s and is intended to demonstrate the effectiveness of the proposed compensation method rather than a universal performance metric. The experimental results demonstrate that the door opening time without compensation is 3.454 s, which is reduced to 3.256 s after applying the proposed method, thereby achieving a time error improvement of 77.95%. These results demonstrate that the proposed approach effectively mitigates time errors caused by startup delays, enabling door motion to more closely follow the preset timing and enhancing overall control accuracy in compliance with EN 14752 standard requirements.

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1. Introduction

Rail transit is a core mode of public transportation. In recent years, many Asian countries have continuously invested substantial resources in the construction and upgrading of various railway systems to enhance transportation efficiency and stimulate economic and tourism development. To integrate domestic railway industry capabilities, promote technological self-reliance, and reduce dependence on foreign systems, the localization and standardization of rolling stock and their key subsystems have become important policy objectives actively pursued by governments.

Within the overall train system, doors serve as the primary interface for passenger boarding and alighting, and their operational stability and safety directly affect train punctuality and operational safety. According to related studies, Sun *et al.* reported that the reliability of door systems plays a critical role in train operation, and further research indicates that up to 50% of transportation accidents are associated with door malfunctions.(1) These findings highlight the significant impact of door failures on railway safety, underscoring the importance of improving door control and diagnostic technologies. Consequently, train door systems must comply with the opening and closing performance requirements specified in the international railway standard EN 14752, and obtain relevant safety certifications such as EN 50126 and EN 50128. In particular, during train operation, the timing accuracy and operational consistency of door opening and closing are critical safety indicators, as any delay or instability may compromise passenger safety and operational efficiency.

The door system investigated in this study is a double-leaf sliding powered door, a structure characterized by high stability and reliable safety performance, and widely adopted in railway systems worldwide. In the process of upgrading existing door control systems in Taiwan, considerations of overall cost and system compatibility often necessitate retaining existing controllers, drive modules, and sensing components. However, the motors and encoders used in current systems are typically based on designs developed more than three decades ago, with limited resolution and signal quality, making it difficult to directly apply conventional control methods that rely on high-precision feedback.

An additional challenge arises from the relatively short effective travel distance of train doors, which is approximately 1.2 m. Achieving smooth motion, consistent speed, and precise compliance with standardized timing requirements within such a limited stroke presents a significant challenge for control systems. The coarse nature of encoder feedback not only results in discontinuous speed estimation but also increases the likelihood of oscillations, error amplification, and response delays in traditional closed-loop control schemes. Therefore, developing a control algorithm that can accommodate low-resolution sensors while maintaining high control accuracy—without replacing existing hardware—has become a critical issue in improving the performance of legacy train door systems.

In the field of brushless DC (BLDC) motor control, numerous speed control strategies have been proposed to improve both dynamic and steady-state performance charactersitics. For example, Jain *et al.* proposed a current-mode control scheme for sensorless BLDC drives, which enhances control performance through effective current feedback and improves stability, particularly under low-speed operating conditions.[2] However, this approach relies heavily on high-resolution sensors and precision measurement hardware, making it unsuitable for the legacy hardware architecture used in existing train door systems. Iizuka *et al.* proposed a sensorless control method based on back electromotive force (EMF) estimation for rotor position detection.[3] Although this method eliminates the need for position sensors, its estimation accuracy degrades significantly at low speed and during startup, and it requires dedicated circuit design, which limits its applicability to train door systems characterized by short travel distance and strict constraints on hardware modification.

Xia *et al.* proposed a control strategy for a four-switch three-phase BLDC motor using a single current sensor, in which an adaptive PI-based algorithm is employed to improve control performance and reduce system complexity.[4] Nevertheless, such methods require the development of complete nonlinear mathematical models and real-time adaptive computation, resulting in high computational complexity. Consequently, they typically depend on high-performance microcontrollers or digital signal processors, which limits their practical applicability in legacy door control systems with constrained computational resources. Yun *et al.* proposed a position control method for low-cost BLDC motors based on Hall sensors and back-EMF characteristics, in which the effective position resolution is enhanced by gear ratio amplification.[5] Although this method is applicable to continuously rotating systems such as automotive intake mechanisms, its control accuracy strongly depends on the gear ratio and accumulated Hall sensor signals. For train door systems with a travel distance of only 1.2 m and stringent timing constraints, achieving sufficient temporal and speed control accuracy within such a short stroke remains difficult, rendering this approach unsuitable for the application considered in this study.

In addition, other control techniques—including model predictive control (MPC) proposed by Kakosimos *et al.*,[6] sliding-mode control by Hou *et al.*,[7] fuzzy logic control by Arulmozhiyal and Kandiban,[8] neural-network-based speed estimation by Chu *et al.*,[9] Kalman-filter-based speed estimation by Zeng and Deng,[10] torque ripple compensation methods proposed by Yuan *et al.*[11] and Huang and Yang,[12] and feedforward–PID hybrid control strategies reported by Wang *et al.*[13] and Eryan *et al.*[14]—have demonstrated promising performance in various applications. However, these approaches generally rely on high-quality feedback signals, high-speed computational platforms, or additional sensing hardware.

Some studies have also focused on adaptive backstepping control for motor speed regulation, which addresses system nonlinearities through recursive control design.[15] Nevertheless, the derivation of the control law is complex and highly sensitive to model parameter accuracy, making it difficult to implement in legacy systems. Disturbance observer (DOB)-based methods have been proposed to compensate for load and friction variations,[16] but such approaches require high-resolution speed or acceleration feedback to ensure estimation accuracy and are therefore unsuitable for environments with low-resolution encoders. Furthermore, reinforcement-learning-based control strategies have been explored to enhance control adaptability;[17] however, these methods demand extensive training data and online learning capability, posing significant implementation challenges for microcontrollers with limited computational resources.

The requirements of the aforementioned methods cannot be satisfied in the legacy train door systems considered in this study, which are characterized by a short travel distance of approximately 1.2 m, low-resolution encoders, and limited microcontroller computational capability. Therefore, it is necessary to develop a speed control strategy that can operate within the existing hardware architecture, impose low computational burden, and maintain satisfactory control accuracy to meet the upgrade demands of current train door systems. On the basis of the above literature review, although existing BLDC motor control methods have demonstrated excellent theoretical and experimental performance characteristics—including current-loop control, sensor-assisted schemes, nonlinear adaptive control, and advanced algorithms such as MPC, sliding-mode control, fuzzy logic, and Kalman filtering—most of these approaches depend on high-resolution feedback, high-performance computational platforms, complex models, or additional hardware support. As a result, they are not applicable to the legacy train door architecture addressed in this work. Under conditions involving a limited travel distance of approximately 1.2 m, coarse encoder resolution, and constrained computational resources, many advanced control strategies are not only difficult to deploy in practice but also unable to deliver their expected performance within the existing hardware framework.

Motivated by these constraints, in this study, we propose a speed control method that can be directly implemented on existing equipment with low computational complexity while effectively improving the timing accuracy of train door operation. The proposed triangular approximation compensation mechanism can be regarded as a time-domain adaptive reference scaling strategy, in which the speed command is iteratively adjusted on a cycle-by-cycle basis to compensate for time delays induced during the startup phase. By integrating the previously proposed variable-step speed adjustment method(18) with the triangular approximation compensation mechanism, the proposed approach effectively suppresses timing errors caused by the startup rising profile, enabling door motion to more closely follow the predefined target and ensuring compliance with the operational performance requirements specified in EN 14752.

2. Simulation Model

In this section, we present the simulation model used to evaluate the proposed speed control and compensation strategy. An integrated motor–mechanism framework is developed in MATLAB/Simulink to reproduce the dynamic behavior of the train door system under low-resolution encoder feedback. The model incorporates the electrical and mechanical characteristics of the DC motor, the H-bridge driver, pulse width modulation (PWM) control, and a multibody door mechanism with friction and load effects. On the basis of this simulation environment, the timing accuracy of door opening and closing operations is analyzed, and the effectiveness of the proposed triangular approximation compensation method in reducing rise-time-induced time deviation is verified in accordance with EN 14752 requirements.

2.1 Integrated motor–mechanism simulation framework in MATLAB/Simulink

To verify the feasibility of the proposed control method, an integrated motor–mechanism simulation framework is developed using the MATLAB/Simulink platform. As shown in Fig. 1,

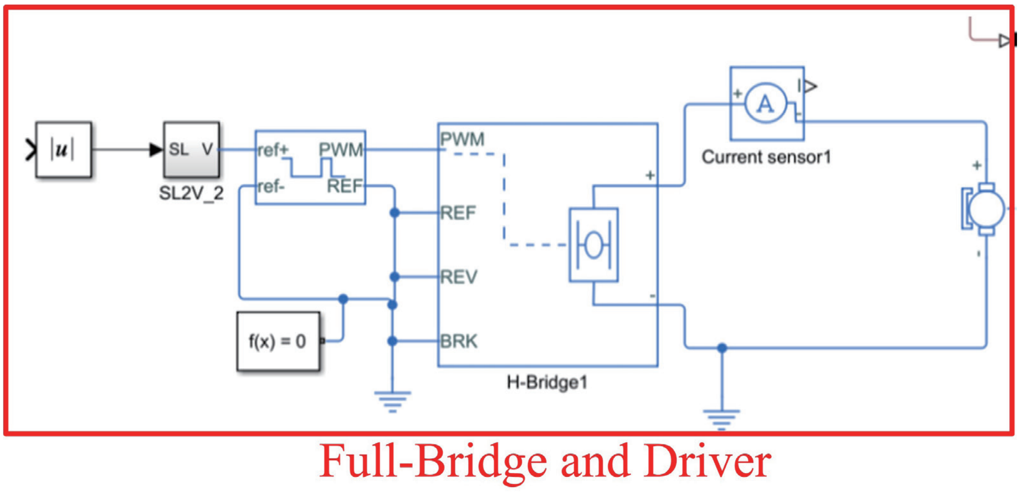

Fig. 1. (Color online) Controller and driver modules of DC motor in Simscape simulation.

the model is designed to ensure that the simulated behavior closely matches the dynamic characteristics of the actual train door system while satisfying the door opening and closing performance requirements specified in EN 14752. This simulation framework is based on the fundamental DC motor dynamic model presented in a previous study;(18) however, to focus on the validation of the proposed control strategy, the associated derivations are presented only in a simplified and summarized form.

The motor model adopts a standard electrical–mechanical equivalent representation. The electrical subsystem consists of resistance, inductance, and back EMF, which are used to describe the transient behavior of the armature current. The mechanical subsystem includes parameters such as rotational inertia, friction terms, and angular velocity to characterize the motor's rotational response under load during door operation. The associated mathematical model is formulated on the basis of fundamental motor principles and derivations reported in previous studies, and the motor current and speed dynamics are described using simplified differential equations [Eqs. (1) and (2)].

$$\int \frac{di}{dt}dt = i \tag{1}$$

$$L\frac{di}{dt} = -Ri + V - e \rightarrow \frac{di}{dt} = \frac{1}{L}\left(-Ri + V - C_e\dot{\theta}\right) \tag{2}$$

The H-bridge driver circuit and the PWM controller are also integrated into the model to simulate the effect of duty cycle on motor output. To prevent controller saturation, the PWM output is constrained within a range of 20–95%, allowing the simulation to reflect the safe operating limits of the actual system. To realistically reproduce the motion behavior of a train door with a short travel distance of 1.2 m, the Simscape Multibody is employed to construct a multibody mechanism model comprising the door panel, rollers, guide rails, and gearbox. Friction and load effects are incorporated to capture the resistance and dynamic characteristics encountered during actual operation. This simulation environment enables the comprehensive observation of startup delay during door opening, steady-state behavior during constant-speed motion, and deceleration transitions at the end of door closing, thereby allowing fair and consistent comparison of different control strategies.

Through this integrated simulation framework, the performance of the proposed variable-step control strategy can be evaluated without relying on high-resolution sensors, and its effectiveness in improving speed tracking and reducing operation time under low-resolution encoder conditions can be verified.

2.2 Simulation of door operation timing accuracy under EN 14752 requirements

According to the EN 14752 standard, the opening and closing times of train doors should fall within a range of 3–5 s, and the door control system must operate reliably and accurately. In this study, the allowable timing error is further constrained to within ±0.1 s to ensure passenger safety and operational efficiency during boarding and alighting. (The ±0.1 s criterion is adopted in this study as an internal performance indicator and is not explicitly specified in EN 14752.) A dynamic simulation model is established to analyze the door closing process. However, in legacy door systems, the limited resolution of the encoder results in a prolonged rise time when applying the previously proposed variable-step speed adjustment method,[18] preventing the controller from reaching the target speed promptly. This startup delay causes a discrepancy between the preset and actual door operation times; even when the target time is set to 3.2 s, the measured completion time is often delayed to more than 3.4 s. Under the adopted internal timing accuracy criterion, these results indicate that under low-resolution feedback conditions, the compensation capability of the original method is insufficient to meet practical timing accuracy requirements. Therefore, it is necessary to further improve the speed command generation strategy. In this study, we employed the previously established variable-step speed control framework and incorporated the proposed triangular approximation compensation mechanism to mitigate the time deviations induced by the startup rise time.

As demonstrated in Fig. 2, the comprehensive driving mechanism of the train door is simulated utilizing the established full-bridge driving architecture. Functional Block 1 is responsible for detecting the door's motion state, including the initial and final positions of the opening and closing operations, respectively, on the basis of the encoder feedback. Then, it transmits the real-time door travel information to the control system. Subsequently, Functional Block 2 calculates the complete door opening and closing cycle time on the basis of the feedback door displacement signal. The proposed speed control module then uses this signal to recalculate the speed command. This recalculation is achieved through the triangular approximation compensation of Function Block 3. Consequently, this process offsets the time deviation caused by the rise time of the original system. The overall control flow is shown in Fig. 3. The *ODCMD* and *CDCMD* denote the compensated speed commands for door opening and closing,

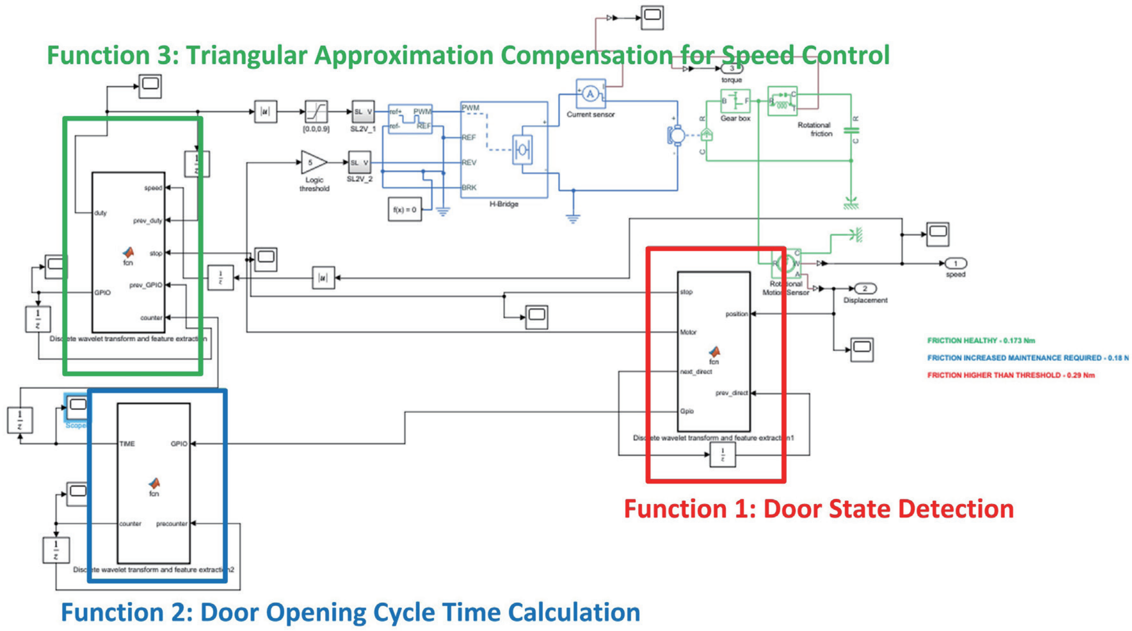

Fig. 2. (Color online) Simscape-based triangular approximation speed command compensation method.

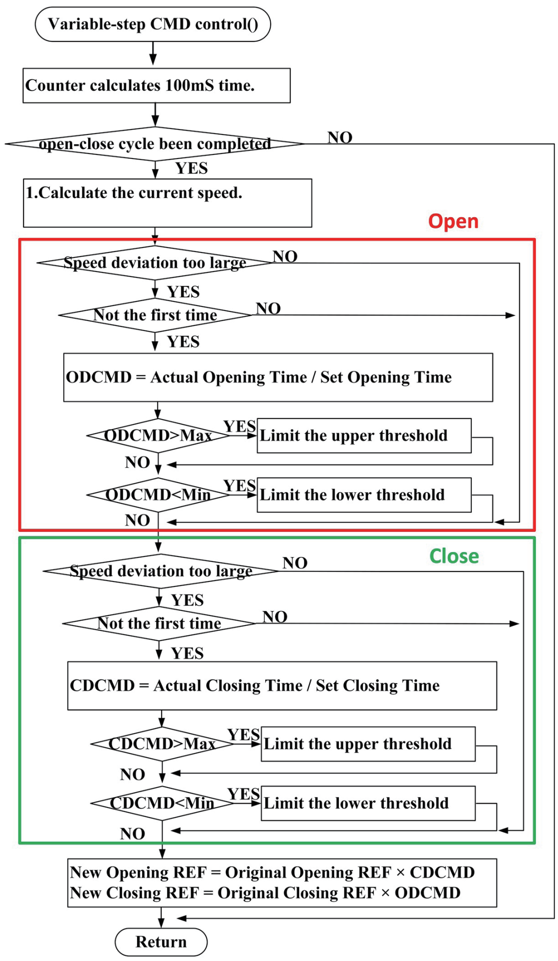

Fig. 3. (Color online) Flowchart of variable-step speed control with triangular-approximation-based time compensation for door opening and closing.

respectively, generated through triangular-approximation-based time scaling. Through this iterative adjustment process, the controller automatically corrects the speed reference, allowing the door operation time to gradually converge toward the specified requirement. The proposed method can enable significant improvement in timing control accuracy for legacy door systems under low-resolution encoder conditions.

As shown in Fig. 4, the previously proposed control scheme exhibits a distinct rise interval in the speed response, preventing the door speed from instantaneously reaching the target value in a “vertical” manner. In other words, although the controller sets the reference speed to achieve door opening within 3.2 s, the actual speed trajectory requires an acceleration phase before reaching the steady-state region. This rise time occupies additional operation time, resulting in a total door opening period longer than the preset value. For example, in the simulated case with a reference speed of REF = 130, the desired opening time is set to 3.2 s, whereas the measured total opening time is approximately 3.3 s, yielding a discrepancy of 0.1 s. Compared with the timing accuracy required in this study, this deviation is non-negligible and indicates that conventional variable-step speed control remains insufficient when rise-time effects are present, necessitating additional compensation mechanisms for correction.

Because the speed command is affected by the rise time during actual operation, the total door opening time becomes longer than the preset value. Therefore, in this study, we propose a triangular approximation compensation approach to modify the speed command so as to compensate for the time deviation caused by the rise time. As shown in Fig. 5, when the target operation time is set to 3.2 s but the measured completion time ranges from 3.3 to 3.4 s, a time-scaling factor can be applied to adjust the speed command accordingly.

The original speed command is uniformly scaled by a factor k, as defined in Eq. (3), to shorten the operation time in the subsequent cycle. The time compensation factor is defined as

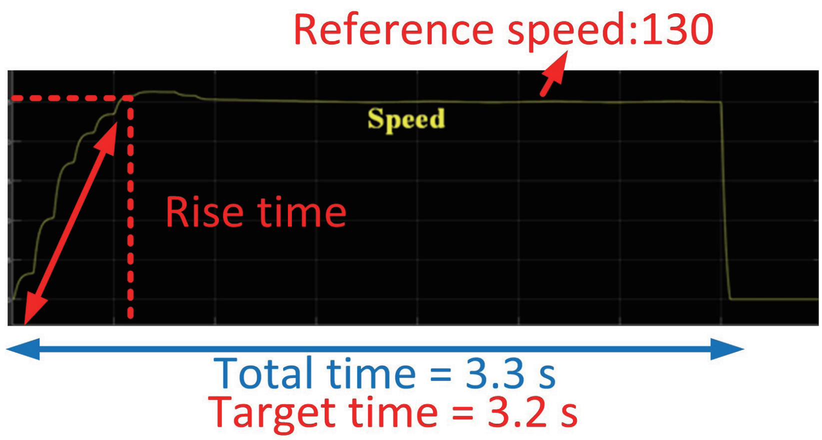

Fig. 4. (Color online) Effect of rise time on total door operation time under variable-step speed control.

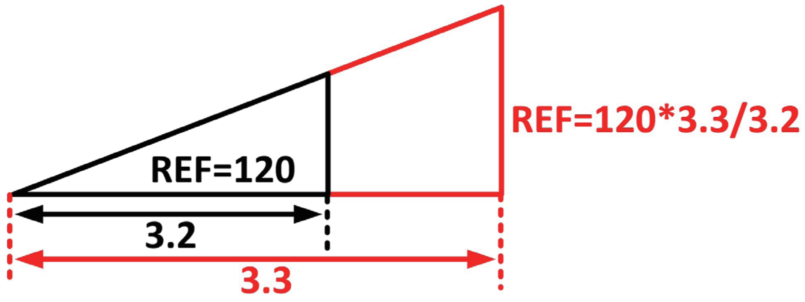

Fig. 5. (Color online) Triangular-approximation-based reference speed scaling for rise-time compensation.

$$K = \frac{T_{actual}}{T_{target}}. \tag{3}$$

For example, when the measured value is T_{actual} = 3.4 s and the preset value is T_{target} = 3.2 s,

$$K = \frac{T_{actual}}{T_{target}} = 1.0625 \tag{4}$$

can be obtained.

Therefore, the original speed command REF = 120 is adjusted as defined in Eq. (5).

$$REF_{new} = K \times REF \tag{5}$$

The system then performs the next door opening operation using the updated speed command of 128 and re-measures the resulting operation time, which serves as the basis for the subsequent proportional adjustment. Through this repeated proportional correction mechanism, the time deviation caused by the rise time can be progressively compensated, allowing the actual door opening and closing time to converge toward the preset target value. As illustrated in Fig. 3, the proposed control process operates with a control period of 100 ms and is triggered by a counter interrupt to execute the variable-step command (CMD) control. Upon entering the routine, the counter first determines whether the current door opening–closing cycle has been completed. If the cycle is not yet complete, only the standard variable-step speed control is applied, and no time compensation is performed. The triangular approximation compensation process is activated only after a complete door operation cycle has been detected.

During the compensation process, the average speed is first calculated on the basis of the encoder signals, and a "speed deviation too large" condition is evaluated to determine whether the deviation between the measured door operation time and the preset value exceeds a predefined threshold. In addition, no compensation is applied during the first operation cycle, which is used solely as a baseline measurement. Time scaling is performed only when the operation is not the first cycle and the deviation exceeds the specified threshold. For the door opening operation, the controller computes the scaling factor as defined in Eq. (6).

$$ODCMD = \frac{Actual\,Opening\,Time}{Set\,Opening\,Time} \tag{6}$$

The calculated *ODCMD* is then examined to determine whether it exceeds the predefined upper and lower bounds (Max and Min, respectively). If the value falls outside this range, it is constrained using the corresponding upper or lower threshold limit. The same procedure is applied to the door closing operation, for which the controller computes the *CDCMD* as defined in Eq. (7).

$$CDCMD = \frac{Actual\,Closing\,Time}{Set\,Closing\,Time} \tag{7}$$

Saturation processing is applied to enforce the upper and lower bounds. After completing the time-scaling calculations for both the opening and closing phases, the system updates the speed commands for the next operation cycle using the corresponding scaling factors. Through this triangular approximation compensation and proportional scaling mechanism, the speed commands for door opening and closing are automatically increased or decreased according to the timing error observed in the previous cycle. The updated reference values are then fed back into the variable-step speed control loop and take effect at the beginning of the next 100 ms control period. Through successive iterations, the actual door opening and closing times gradually converge to the preset target values and remain within the safety requirements specified by applicable standards.

As shown in Fig. 6, the simulation results comprehensively illustrate the dynamic variations of PWM duty cycle, speed, and motor current during the door opening and closing processes, clearly reflecting the effect of the variable-step control strategy on the overall motion behavior. In the figure, the speed is represented by the number of encoder pulses per 0.1 s, the duty cycle is expressed in normalized form (e.g., 0.6 corresponds to 60%), and the current scale approximately corresponds to 1 A. During the door opening phase (left-hand side), the PWM duty cycle increases rapidly at the startup stage to overcome static friction and provide sufficient driving force, allowing the speed to rise quickly from zero. As the speed approaches the target range, the controller gradually reduces the duty-cycle adjustment magnitude, resulting in a smoother speed profile and stabilized current, which exhibits the typical characteristic of a rapid rise followed by steady-state operation.

As demonstrated in Fig. 7, the door opening time in the initial operation cycle is considerably longer than the preset target value of 3.2 s, with the measured result being 3.454 s. This indicates a clear discrepancy between the actual and desired operation times. The underlying causes and

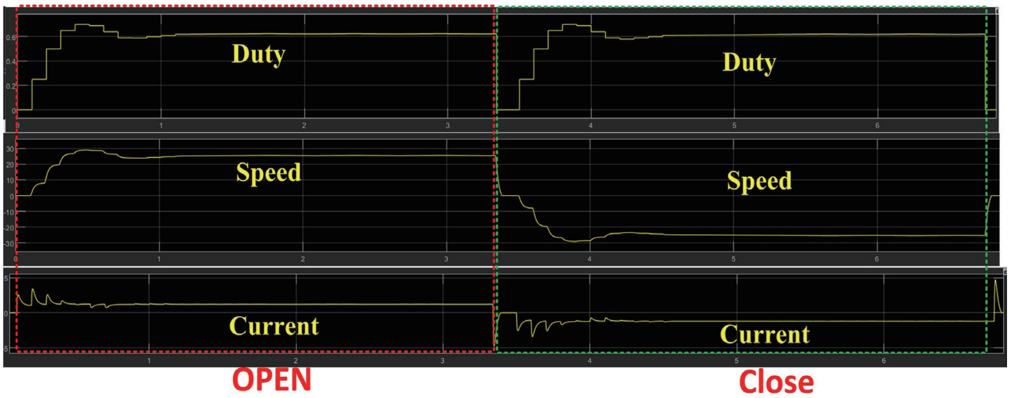

Fig. 6. (Color online) Simulated PWM duty cycle, speed, and motor current during door opening and closing under variable-step speed control.

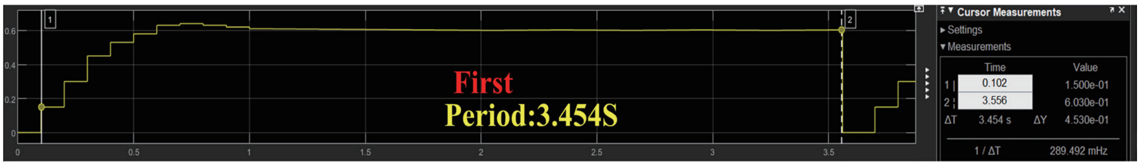

Fig. 7. (Color online) First-cycle door opening period under variable-step speed control without triangular compensation.

implications of this timing deviation will be thoroughly examined and analyzed in the subsequent sections. The convergence behavior of variable-step speed control with triangular compensation during the door opening period is demonstrated in Fig. 8. The simulation results comprehensively illustrate the dynamic variations of PWM duty cycle, speed, and motor current during the door opening and closing processes. These results clearly reflect the effect of the variable-step control strategy on the overall motion behavior. A comprehensive evaluation of the outcomes indicates that the proposed triangular approximation compensation method offers a significant enhancement. In Fig. 8, the speed is represented by the number of encoder pulses per 0.1 s, the duty cycle is expressed in normalized form (e.g., 0.6 corresponds to 60%), and the current scale approximately corresponds to 1 A. The uppermost waveform represents the operation time of each door opening cycle, while the waveform below illustrates the corresponding PWM duty cycle variation. The two bottom waveforms present detailed speed commands and time measurement results for the first and tenth door opening operations, respectively, enabling a direct comparison of system behavior before and after compensation.

During the initial operation (Cycle 1), the system has not yet acquired sufficient information to perform compensation, and the total door opening time is approximately 3.454 s, which is notably longer than the preset target of 3.2 s. This deviation is primarily caused by the rise time and reflects the timing offset that exists in the conventional control scheme under low-resolution

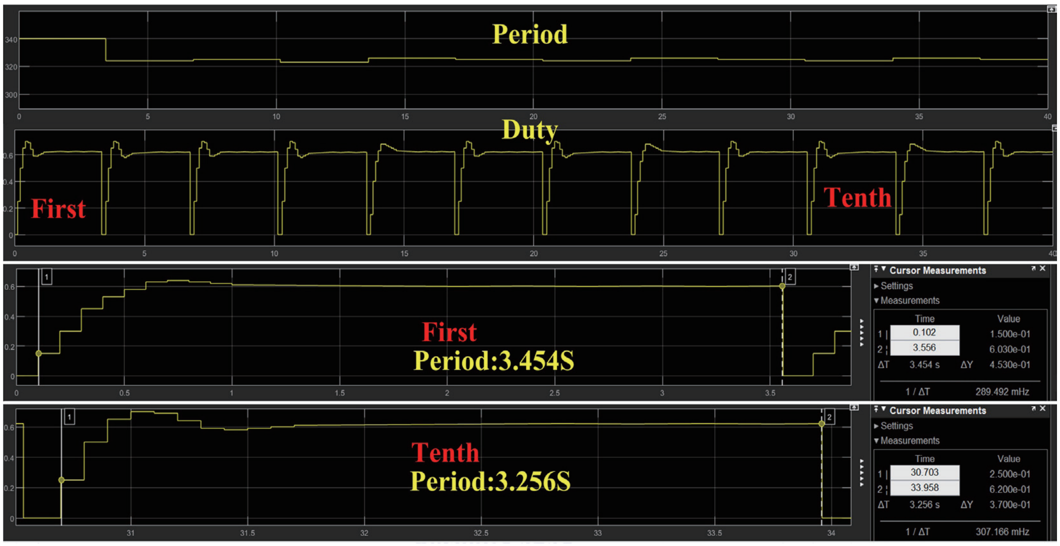

Fig. 8. (Color online) Convergence of door opening period through iterative variable-step speed control with triangular compensation.

encoder conditions. After applying the proposed triangular approximation compensation and proportional correction, the controller automatically updates the speed reference in each cycle, allowing subsequent operations to more closely approach the target time. By the tenth iteration, the door opening time is significantly reduced to 3.256 s, with the deviation substantially minimized and the control accuracy effectively improved. The cycle waveforms also exhibit a stable convergence trend, indicating that the compensation algorithm exhibits good iterative consistency and repeatability. Overall, the proposed compensation strategy enables legacy train door systems to progressively converge toward the preset operation time without replacing the existing sensors, successfully enhancing timing control accuracy while satisfying the requirements specified in EN 14752.

To evaluate the effectiveness of the triangular approximation compensation method in improving door opening time accuracy, we used a target opening time of 3.2 s as the reference and compared the measured results from the first and tenth operation cycles. The simulation results show that the door opening time in the first operation cycle is 3.454 s, which exceeds the target value by 0.254 s, indicating a significant deviation in the original control strategy caused by the rise time. After multiple iterations of compensation, the door opening time in the tenth operation cycle is reduced to 3.256 s, with a deviation of only 0.056 s from the target time.

On the basis of the improvement ratio formula defined in Eq. (8), it can be observed that the proposed method successfully reduces the time error by approximately 78%. These results demonstrate that, through periodic measurement and the triangular approximation compensation mechanism, the system is able to progressively correct the speed command, allowing the door opening time to effectively converge to the preset target value. As a result, the timing control accuracy of legacy train door systems operating under low-resolution encoder conditions is significantly improved. The reported improvement rate is calculated on the basis of a target time of 3.2 s under fixed load conditions and is primarily intended to illustrate the effectiveness of the proposed method in compensating for startup-induced delays.

$$Improvement\ rate = \frac{0.254 - 0.056}{0.254} \times 100\% \cong 77.95\% \quad (8)$$

3. Hardware Design

The variable-step speed control method proposed in this study is first verified through simulation using a physical model developed in MATLAB/Simscape. The simulation results indicate that the motor speed response, PWM duty cycle, and current waveforms of the train door system are all consistent with the expected behavior, confirming that the proposed control strategy can effectively achieve smooth and stable door motion. On the basis of these results, a hardware implementation of the door speed control system is further designed and realized to apply the algorithm to a practical system.

On the basis of the hardware architecture designed in the previously submitted work,[18] as shown in Fig. 9, the control circuit board can be mainly divided into three functional sections. The upper-left section comprises the I/O and analog-to-digital conversion (ADC) sensing circuitry, which is responsible for receiving external sensor signals and converting analog information into digital data for real-time state monitoring and processing by the microcontroller unit (MCU). The lower-left section contains the MCU main control unit, whose primary functions include executing the proposed variable-step speed control algorithm, processing

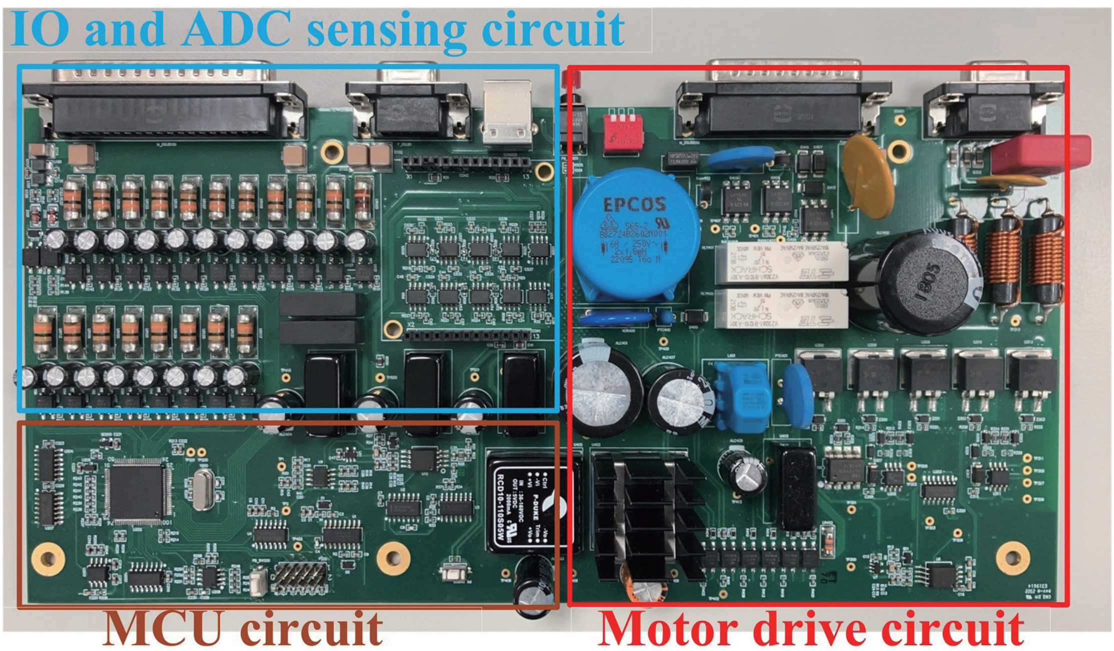

Fig. 9. (Color online) Hardware architecture of train door control board.[18]

sensor signals, generating PWM control commands, and coordinating internal and external system communications.

The right-hand side of the circuit board comprises the motor driver module, including an H-bridge and power MOSFETs, which provide the high-current output required to drive the motor. Capacitors and inductors are also incorporated to suppress power ripple and electromagnetic interference, ensuring stable operation under dynamic load conditions. As shown by the PWM signals generated by the MCU, this module regulates the motor speed and rotation direction, enabling the precise and reliable control of the train door motion.

As shown in Fig. 10, a scaled-down train door test platform is constructed in the laboratory in this study. The platform mainly consists of three components: the door mechanism unit the door panel, and the door control unit (DCU). The door mechanism unit, shown in the upper part of the figure includes the driving motor, reduction mechanism, guide rails, and transmission components, which provide the driving force for the door panel and ensure smooth linear sliding motion. The central section shows a double-leaf sliding door panel, which is represented by a model panel in this study to emulate the mass and motion behavior of an actual train door. The lower-left section corresponds to the DCU, which contains the control circuit board responsible for receiving sensor signals, executing the speed control algorithm, generating PWM commands, and driving the motor through an H-bridge.

This integrated experimental platform is capable of simulating door opening and closing operations, and supports the integration of speed control, cycle time measurement, and obstacle detection functions. As a result, the proposed control strategy can be validated under a quasi-realistic experimental environment. The scaled-down experimental platform preserves the key dynamic characteristics of an actual train door system, including comparable travel distance, transmission structure, friction-dominated load behavior, and low-resolution encoder feedback, and is therefore suitable for validating the proposed control strategy.

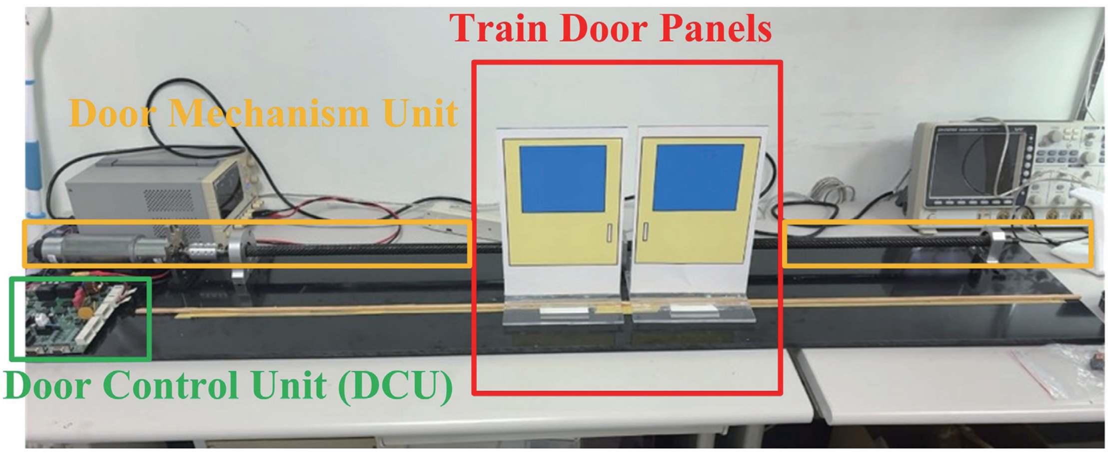

Fig. 10. (Color online) Experimental setup of train door system.

4. Experimental Results and Discussion

Owing to the limited resolution of the encoder, experimentally measured speed waveforms are discontinuous and less representative, whereas motor current provides a more reliable and repeatable indicator of dynamic behavior under practical operating conditions. As shown in Fig. 11, the measured motor current waveforms of an actual train door during the opening and closing operations are presented. According to the experimental results, the door opening and closing times are approximately 3.22 and 3.23 s, respectively, both of which fall within the 3–5 s range required by EN 14752. These results demonstrate that the proposed control method effectively satisfies the timing specifications for train door operation.

From the current waveforms, the typical dynamic behavior can be clearly observed. At startup, a pronounced inrush current is generated to overcome initial static friction and initiate door motion. During the steady-travel phase, the current exhibits periodic fluctuations, reflecting the periodic torque demand caused by mechanical load variations and viscous friction. When the door panel reaches the end position and comes to a stop, the current rapidly decreases to a low level, indicating that the driver successfully executes deceleration and stopping control.

A comparison between the measured waveforms and the previously presented simulation results reveals a high degree of consistency in terms of startup inrush behavior, steady-state amplitude, and transient response during stopping. This agreement confirms that the Simscape-based dynamic model developed in this study accurately represents the behavior of the actual system and further validates the feasibility and reliability of the variable-step speed control strategy when implemented in a real train door system under similar operating conditions.

The variable-step speed control method proposed in this study has been successfully validated through both simulation and experimental results under the constrained conditions of low-resolution encoders and legacy door mechanisms, and it achieves the door opening and closing time accuracy required by EN 14752. The measured experimental waveforms exhibit a

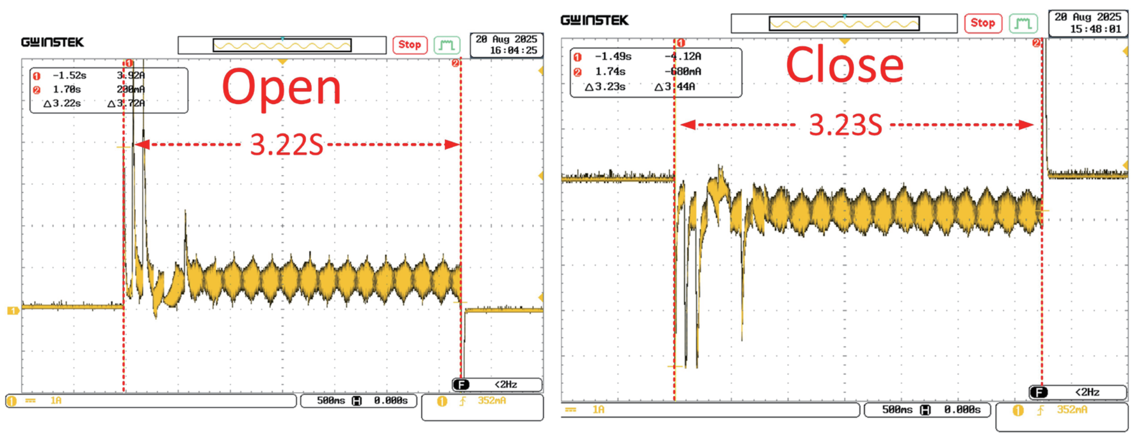

Fig. 11. (Color online) Measured motor current waveforms during door opening and closing operations.

high degree of agreement with the simulation results, with only minor discrepancies in current distribution arising from differences in friction coefficients and lubrication conditions. These results indicate that the developed model exhibits good accuracy and predictive capability. Compared with conventional fixed-step control methods, the proposed approach significantly reduces rise time and steady-state oscillations, resulting in smoother door operation and improved timing consistency.

Although the door travel distance considered in this study is limited to approximately 1.2 m and is based on a legacy hardware architecture, the validation results demonstrate that the proposed triangular approximation compensation combined with variable-step speed control exhibits strong generality and has the potential to be extended to other types of train door systems. Future work will further investigate the adaptability of the proposed method under different transmission mechanisms, door masses, and load conditions, and will evaluate the feasibility of integrating additional sensing technologies, such as door closing force detection and flexible obstacle sensing, to enhance overall system safety and robustness.

In this study, we addressed the limitations of legacy train door systems, particularly the insufficient encoder resolution and restricted control accuracy, by proposing a variable-step speed control method incorporating a triangular approximation compensation mechanism. Under low-resolution feedback conditions, conventional fixed-step or linear speed adjustment strategies tend to suffer from prolonged rise time and inaccurate speed tracking, leading to significant discrepancies between the preset and actual door operation times. Such deviations make it difficult to satisfy the timing accuracy requirements specified in EN 14752. To overcome these issues, the proposed method introduces cycle-to-cycle error feedback and dynamic PWM duty-cycle adjustment, enabling the continuous correction of the speed command and progressive convergence toward the target operation time.

A comprehensive Simscape-based dynamic model of the train door system was developed, including the motor, gearbox, transmission mechanism, friction characteristics, and door panel motion. Simulation results demonstrate that the proposed variable-step control strategy effectively shortens the speed rise time, reduces steady-state oscillations, and improves overall control accuracy. Without compensation, the door opening and closing cycle was set to 3.2 s, but the simulated operation time reached 3.454 s. After incorporating the triangular approximation compensation, the operation time was reduced to 3.256 s by the tenth iteration, corresponding to a time error improvement rate of 77.95%. These results clearly illustrate the effectiveness of the proposed compensation mechanism in mitigating rise-time-induced timing errors under low-resolution encoder conditions.

Experimental validation was further conducted using a laboratory-scale train door test platform. The measured motor current waveforms exhibit characteristic startup inrush current, stable driving behavior during steady motion, and rapid current decay at stopping, which are consistent with the simulation trends. The measured door opening and closing times of approximately 3.22–3.23 s comply with the EN 14752 requirements. Minor discrepancies between simulation and experimental results are mainly attributed to variations in friction coefficients and lubrication conditions, which are difficult to model precisely but do not affect the overall control performance trends.

5. Conclusion

In this paper, we presented a variable-step speed control method with triangular approximation compensation for legacy train door systems operating under low-resolution encoder feedback and limited computational resources. Both simulation and experimental results confirm that the proposed approach achieves the door opening and closing time accuracy required by EN 14752 without modifying the existing hardware. Compared with conventional fixed-step control strategies, the proposed method demonstrates faster convergence, reduced oscillation, and significantly improved timing accuracy. Although the experimental validation is conducted on a legacy door system with a limited travel distance of approximately 1.2 m, the proposed control strategy exhibits good generality and scalability. Future work will focus on extending the proposed method to different door mechanisms and transmission structures, as well as investigating its adaptability under varying door mass and load conditions. In addition, the integration of supplementary sensing technologies, such as door closing force detection, will be explored to further enhance system safety and robustness. This feature is particularly valuable for upgrading legacy train door systems, as it allows existing hardware to be retained while achieving improved timing accuracy through software-based compensation.

References

1 Y. Sun, Y. Cao, and L. Ma: IEEE Intell. Transp. Syst. Mag. **13** (2021) 107. https://doi.org/10.1109/MITS.2019.2926366
2 P. K. Jain, W. Kang, H. Soin, and Y. Xi: IEEE Trans. Power Electron. **17** (2002) 649. https://doi.org/10.1109/TPEL.2002.802181
3 K. Iizuka, H. Uzuhashi, M. Kano, T. Endo, and K. Mohri: IEEE Trans. Ind. Appl. IA-**21** (1985) 595. https://doi.org/10.1109/TIA.1985.349715
4 C. Xia, Z. Li, and T. Shi: IEEE Trans. Ind. Electron. **56** (2009) 2058. https://doi.org/10.1109/TIE.2009.2014307
5 S. Y. Yun, H. J. Lee, J. H. Han, and J. Lee: Proc. 6th Int. Conf. Electromagnetic Field Problems and Applications (2012) 1. https://doi.org/10.1109/ICEF.2012.6310322
6 P. Kakosimos, M. Beniakar, Y. Liu, and H. Abu-Rub: Proc. IEEE Applied Power Electronics Conf. and Exposition (2017) 1880. https://doi.org/10.1109/APEC.2017.7930954
7 P. Hou, X. Wang, and Y. Sheng: Proc. Chinese Control And Decision Conf. (2019) 3151. https://doi.org/10.1109/CCDC.2019.8832483
8 R. Arulmozhiyal and R. Kandiban: Proc. Int. Conf. Computer Communication and Informatics (2012) 1. https://doi.org/10.1109/ICCCI.2012.6158919
9 K. Chu, K. Chew, and Y. Chang: Proc. IEEE Int. Colloq. Signal Processing & Its Applications (2022) 35. https://doi.org/10.1109/CSPA55076.2022.9781875
10 H. Zeng and M. Deng: Proc. IEEE Int. Conf. Information Systems and Computer Aided Education (2024) 1033. https://doi.org/10.1109/ICISCAE62304.2024.10761879
11 W. Yuan, Y. Wang, Z. Zhang, and R. Liang: Proc. IEEE Int. Conf. Power Electronics and Motion Control (2016) 2831. https://doi.org/10.1109/IPEMC.2016.7512746
12 C.-L. Huang and S.-C. Yang: Proc. IEEE Int. Future Energy Electronics Conf. (2021) 1. https://doi.org/10.1109/IFEEC53238.2021.9661795
13 H. Wang, J. Tian, and Y. Yang: Proc. Int. Conf. Electronics, Integrated Circuits and Communication Technology (2025) 476. https://doi.org/10.1109/EICCT65471.2025.11100022

14 C. Eryan, I. Rosyadi, Y. Y. Nazaruddin, and A. M. Burohman: Proc. Int. Conf. Instrumentation, Control, and Automation (2025) 343. https://doi.org/10.1109/ICA65945.2025.11252522

15 H. Lin, W. Yan, J. Wang, Y. Yao, and B. Gao: Proc. Int. Conf. Mechatronics and Automation (2009) 335. https://doi.org/10.1109/ICMA.2009.5246576

16 H. Li, S. Li, and Y. Yan: Proc. IEEE Int. Conf. Predictive Control of Electrical Drives and Power Electronics (2023) 1. https://doi.org/10.1109/PRECEDE57319.2023.10174295

17 F. Rossi, G. Gruosso, and G. S. Gajani: Proc. IEEE EUROCON Int. Conf. Smart Technologies (2023) 181. https://doi.org/10.1109/EUROCON56442.2023.10198954

18 C. Y. Liu, M. T. Yeh, C. C. Chiu, and Z. Y. Syu: Sens. Mater. **38** (2026) 2567. https://doi.org/10.18494/SAM5764