LQG-based optimal control approach of an electronic throttle valves using DC servo system

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ABSTRACT

A direct current (DC) motor is used for automotive electronic throttle valves (AETV) to adjust incoming air into the engine's combustion system, which has many advantages such as smooth, fast response, and simplicity. However, high-accuracy tracking control for AETV faces various obstacles because of the nonlinear features, hard identification, and noise. In this paper, a model of the AETV with four states in the form of a state space is developed. Then, a Kalman filter is formulated to eliminate the impact of measurement noise. The Kalman filter gain is obtained via the solve the linear quadratic gaussian (LQG) equation. Next, the optimal control based linear quadratic regulation (LQR) and Kalman filter are presented in which the control gain is constructed by the Riccati equation with the assistance of MATLAB/Simulink software. Finally, simulation studies are conducted to demonstrate the efficiency of the suggested method for the AETV system with other control strategies.

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1. INTRODUCTION

The direct current (DC) servo system is suitable for numerous applications in industry environments such as robot manipulator [1] [2], mobile robot [3], [4], automotive industry [5]-[7], fuel cell system [8], [9], and load simulator [10], [11]. Especially, in automotive engineering, the automotive electronic throttle valves (AETV) play a vital role in adjusting the air intake for the engine, which ensures the power, fuel consumption, and the effectiveness of the engine [12]. However, conventional throttle regulation mechanisms are frequently affected by several drawbacks and failures. On the other hand, due to the influences of nonlinear negative factors such as gear backlash, static and dynamic friction, discontinuous nonlinear springs, and measurement noise disturbances, AETV control technology faces significant challenges, particularly in ensuring the throttle plate closely tracks the reference target generated by the pedal. Hence, the development of the advanced controller for electronic throttle valves (ETV) is essential to achieve stability, reliability, and high efficiency.

To enrich the control performance of the AETV, various control methodologies have been proposed, for instance, proportional-integral-derivative (PID) control [13], [14], backstepping control [15], [16], intelligent control [17]-[19] and sliding mode control (SMC) [20], [21]. In [15], an adaptive finite-time backstepping control approach was proposed for AETV to satisfy the stringent standards for tracking performance. In [19], a self-learning PID powered by neural network techniques was presented for the

AETV. In [21], the authors reported an observer-based continuous fast nonsingular terminal SMC for an automobile electronic throttle to ensure the precise tracking despite uncertainties and perturbations. Even though these control strategies can achieve good tracking control performance under several working conditions of AETV systems, there remains a gap, such as the lack of an optimal control approach.

To overcome the effects of the measurement noise, an effective method is the Kalman filter [22], which estimates the unmeasurable variable states and eliminates the measurement noise of sensors. In fact, a simple linear quadratic regulation (LQR) combined with a Kalman filter could be deployed to stabilize and enhance the control system. In [23], a LQR-based intelligent algorithm was suggested for balancing a rotary inverted pendulum, however, the measurement noise was neglected. In [24] and [25], the descriptor Kalman filter was presented to tackle the impacts of the measurement noise. Therefore, a Kalman filter is adopted to obtain a clear output signal, and an LQR is designed to enhance tracking performance, which is crucial.

In this paper, the major innovations can be listed by: i) A new LQR is utilized to guarantee the AETV trajectory to obtain the outstanding performance compared to the PID and SMC controller; ii) The system measurement noise disturbance is eliminated by a Kalman filter and thus the tracking qualification of the AETV is effectively improved; and iii) The stability analysis of the whole closed-loop AETV system and the efficiency of the suggested control strategy are confirmed by the simulation evaluation in MATLAB/Simulink.

The paper organization is described as follows: i) The mathematical model of the AETV system is given in the section 2; ii) The Kalman filter-based LQR controller is presented in the section 3; iii) The simulation setup and analyzed results are described in the section 4; and iv) Finally summaries are highlighted in the section 5.

2. PROBLEM DESCRIPTION

The plant under study is the electronic throttle valve, which comprises a DC motor, a motor driver, a gearbox, a valve plate, an angle sensor, and a variable-stiffness spring. The configuration of DC motor and AETV is displayed in Figure 1(a) and 1(b), respectively. In fact, the DC motor includes two parts: armature and field part. The mathematical model of the presented system can be expressed by the combination of a DC motor and a throttle plate mathematic model as (1)-(3) [26].

$$J_{eq}\ddot{\theta} + b_m\dot{\theta} = T_a - T_m, T_a = K_t i \tag{1}$$

$$L\frac{di}{dt} + Ri = u - K_e\dot{\theta} \tag{2}$$

$$J_t\ddot{\theta}_t + b_t\dot{\theta}_t = T_o - T_L \tag{3}$$

Where u is an external voltage, so-called, control signal of the motor, J_{eq} and J_t are the rotor and throttle plate inertia, θ and θ_t denote the angle of rotation of the output shaft and throttle opening angle, b_m and b_t are a damping factor of motor and throttle plate, T_m and $T_o = NT_m$ represent the torques of gear box, N is gear ratio, T_L is external torque. K_t and K_e define the torque and the back electromotive force coefficient.

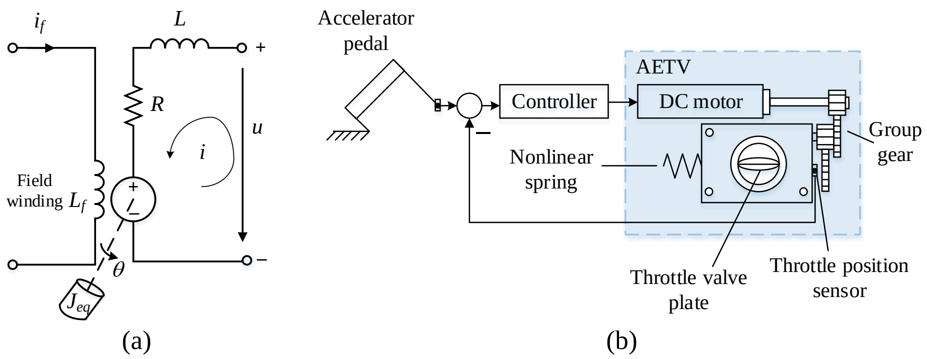

Figure 1. Configuration of the presented system: (a) DC motor and (b) AETV system

Here in, substituting (1) into (3) by removing θ, the modeling in the state space is used to describe the ATEV via the system identification toolbox in MATLAB. The state space of the AETV using a DC motor can be described as (4).

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + w(t) \\ y(t) = Cx(t) + v(t) \end{cases} \tag{4}$$

Where A, B, and C denote the system matrix, input matrix, and output matrix, respectively. $x(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T$ is the state vector, $u(t)$ is a control input signal. $w(t)$ and $v(t)$ are the system noise matrix and measurement noise, respectively.

Remark 1: In this paper, the aim of an AETV control system is to design a control law u that drives the output position p_1 (the throttle plate) to the desired trajectory p_{1d} (generated by the pedal) under the measurement noise. The proposed optimal control based on the LQR and Kalman filter is investigated to obtain high efficiency in the AETV system.

3. LQG-BASED OPTIMAL CONTROL

In this section, a suggested Kalman filter is first formulated on the premise of state space modeling. Next, a linear quadratic regulator (LQR) controller is constructed to stabilize the position output. Herein, the state feedback form Kalman filter is used for the LQR controller to eliminate the effect of the measurement noise. Hence, the control performance is enhanced in different working conditions. The structure of the suggested method is depicted in Figure 2. The linear quadratic gaussian (LQG) controller consists LQR controller and Kalman filter, which are presented in the subsection below.

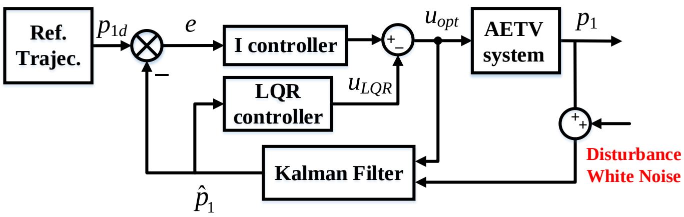

Figure 2. Draw of the proposed control methodology

3.1. Design Kalman filter

Considering the AETV system described in (4), the Kalman filter is constructed to reduce the impact of measurement noise, and then, the control efficiency can be improved. The description of the Kalman filter is presented as (5).

$$\begin{cases} \dot{\hat{x}}(t) = [A\hat{x}(t) + Bu(t)] + E[y(t) - \hat{y}(t)] \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{5}$$

Where $\hat{x}(t)$ and $\hat{y}(t)$ are the estimation of the system states x and output state y, respectively. E defines the Kalman gain vector. E can be calculated by (6).

$$E = FC^T\Phi^{-1} \tag{6}$$

Where $\Phi = E[vv^T]$ denotes the covariance of the measurement noise, F is reached by solving the matrix algebraic Riccati equation (ARE) and a positive definite matrix, as in (7).

$$A^T F + FA - FB\Phi^{-1}B^T F + \Psi = 0 \tag{7}$$

Where $\Psi = E[wwT]$ defines the covariance of the system noise. It is noteworthy that the distribution of measuring and the system follows a multivariate gaussian.

Remark 2: To solve the Riccati equation, there are two methods: by manual and by using MATLAB software. The former is applied to the second-order system. Meanwhile, the latter is used for the higher-order system and is used in this paper. The MATLAB-Mfile code for Kalman filter design is expressed by the following:

```
>> Ψ = 10^(-5)*diag([1 1 1 1]);
>> Φ = 0.1;
>> S = diag([1 1 1 1]);
>> E=lqe(A,S,C,Ψ,Φ)
```

Where S defines the unit matrix.

3.2. Design LQR

Considering the AETV system described in (4), the LQR controller is constructed as (8).

$$u_{LQR} = -Gx \tag{8}$$

Where G defines the LQR gain vector. G can be calculated by (9).

$$G = -m^{-1}B^TP \tag{9}$$

Where m is a positive constant, P is achieved by solving the matrix ARE and obtaining a positive definite matrix, as in (10).

$$A^TP + PA - PBm^{-1}B^TP + N = 0 \tag{10}$$

Where $N \geq 0$.

It is noted that the control law of the LQR controller is formulated to satisfy the cost function given by (11).

$$J(u) = \frac{1}{2}\int_{t_0}^{t_f}[x^T(t)Qx(t) + u^T(t)mu(t)]dt \tag{11}$$

The MATLAB-Mfile code for LQR design is expressed by:

```
>> N=diag(C.*C);
>> m=1;
>> G=lqr(A,B,N,m);
```

The final control law can be designed as (12).

$$u_{opt} = K_{opt}\int edt - Gx \tag{12}$$

Where K_{opt} defines the designed control gain, $e = p_d - \hat{p}_1$ is the tracking error.

4. RESULTS AND DISCUSSION

4.1. Simulation setup

In this subsection, the simulation and experiment results are conducted to demonstrate the efficiency of the proposed method, known as, LQG controller. For simulating the different working conditions, two case studies are investigated by providing the desired signals, including sinusoidal and square wave pulse trajectories. In this paper, the matrices A, B, and C describing AETV can be identified as follows [19]:

$$A = \begin{bmatrix} 1.049 & -1.055 & -1.48 & -1.616 \\ -0.1046 & 1.885 & 1.312 & 1.394 \\ 0.07572 & -0.8545 & -0.1604 & -1.245 \\ 0.02226 & -0.1604 & -0.2187 & 0.7565 \end{bmatrix}$$
$$B = \begin{bmatrix} -0.01709 \\ 0.01275 \\ -0.0127 \\ -0.002276 \end{bmatrix}$$
$$C = [-856.7 \quad -267.7 \quad -11.66 \quad 1.028]$$

Figure 3 illustrates the simulation configuration of the control AETV system. For comparison with the proposed strategy, two other methods—PID and sliding mode controller (SMC)—are also provided. The parameter gains for these controllers are as follows:

PID [13]: $K_P = 0.4$, $K_i = 0.12$, and $K_D = 0$ is the control gain of PID controller which is designed as (13).

$$u = K_p e + K_d \dot{e} + K_i \int_0^t e(t)dt \tag{13}$$

SMC [26]: This controller contains the sliding surface $s = B^T P_s x$, and the control law $u = -(B^T P_s B)^{-1} B^T P_s A x - \lambda (B^T P_s B)^{-1} sign(s)$.

$$\lambda = 0.5;\ P_s = \begin{bmatrix} 7.4496 & 1.2493 & 1.0782 & 1.1384 \\ 1.2493 & 0.3952 & 0.2108 & 0.3252 \\ 1.0782 & 0.2108 & 0.3854 & 0.2280 \\ 1.1384 & 0.3252 & 0.2280 & 0.4286 \end{bmatrix}$$

Proposed method: $K_{opt} = 0.13$. The Kalman filter gain and state feedback gain of LQR controller are computed via the assistance of the MATLAB software as follows:

$$G = \begin{bmatrix} 0.0830 \\ -0.2383 \\ -0.9590 \\ 1.0364 \end{bmatrix};\ E = \begin{bmatrix} -25.1948 \\ 5.4161 \\ 13.2827 \\ 22.5868 \end{bmatrix}^T$$

Two case studies are carried out to confirm the effectiveness of the proposed control AETV system despite the measurement noise in Figure 4. The desired signals are a sinusoidal signal and a square pulse signal, which are given in case studies 1 and 2.

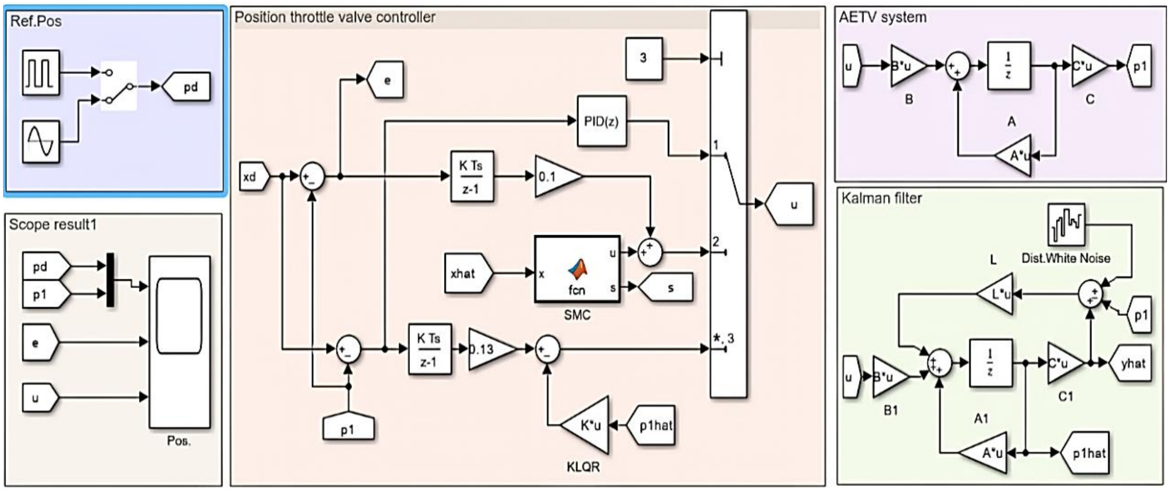

Figure 3. Control system design in MATLAB/Simulink

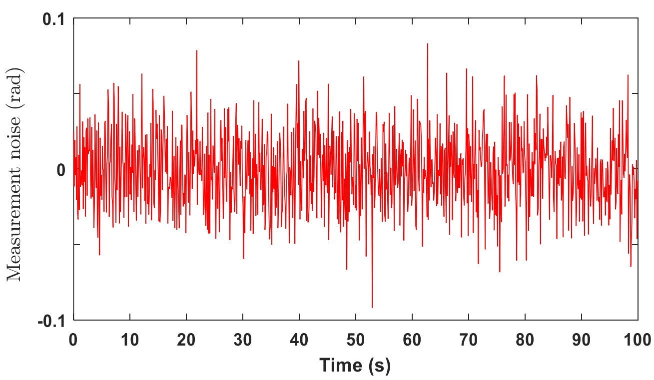

Figure 4. Measuring noise

4.2. Results and discussion

4.2.1. Case study 1

In this case study, the target trajectory of the AETV system is provided as a square wave signal with a 50% duty cycle and an amplitude setting of π (rad). The achieved results are presented in Figure 5. Figure 5(a) displays the tracking efficiency of three algorithms. As seen in Figure 5(a), the suggested method provides outstanding quality compared to PID and SMC. Figure 5(b) depicts the tracking errors, further evidencing the superior quality of the suggested controller with the smallest tracking error. The control efforts of the relevant methods are shown in Figure 5(c).

4.2.2. Case study 2

In this case study, the desired trajectory of the AETV system is given as $p_d = \frac{\pi}{2} sin\left(\pi t - \frac{\pi}{2}\right) + \frac{\pi}{2}(rad)$. The simulation results are exhibited in Figure 6. Figure 6(a) displays the tracking efficiency of three controllers. As seen in Figure 6(a), the PID controller brings the worst tracking qualification compared to the proposed strategy and SMC. Figure 6(b) depicts the tracking errors, in which the suggested method has the smallest tracking error. The control efforts of the three controllers are displayed in Figure 6(c). To validate the efficiency of the suggested methodology, performance indexes including root mean square error (RMS) and maximum error (MAE) are presented in Table 1. From Table 1, it reconfirms that the proposed control strategy provides the best qualification and handles the effect of measurement noise as compared to the two other presented controllers.

(a)
(b)
(c)

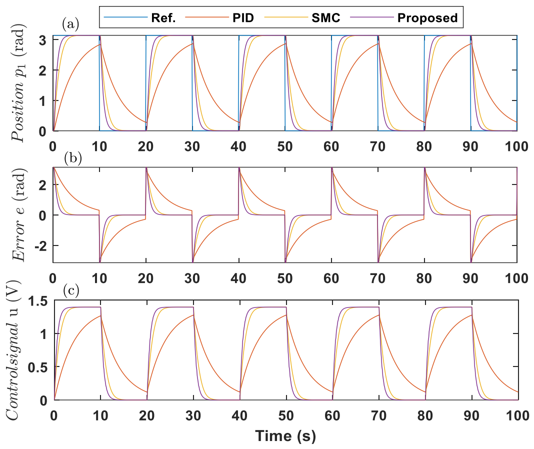

Figure 5. Performance of three controllers in case study 1: (a) position tracking, (b) tracking error, and (c) control input signal

(a)
(b)
(c)

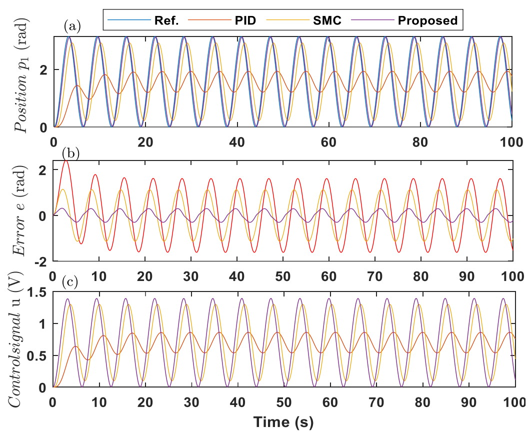

Figure 6. Performance of three controllers in case study 2: (a) position tracking, (b) tracking error, and (c) control input signal

Table 1. The performance of other control strategies

Controllers	Case study 1		Case study 2	
	RMS	MAE	RMS	MAE
PID	1.3993	3.1416	1.1396	1.7906
SMC	0.8754	3.1416	0.7993	1.1290
Proposed	0.7214	2.8715	0.2036	0.3023

5. CONCLUSION

In this paper, the LQG-based optimal control design is investigated for the AETV system in the presence of measurement noise. What's more, the Kalman filter is formulated to reject the influence of measurement noise and supply the estimation states to the main controller. The LQR control approach is performed by the solve Riccati equation and obtaining the optimal gain to enrich the system performance. The MATLAB/Simulink is utilized to confirm the efficiency and applicability of the proposed methodology. In future work, the validation of the proposed method in the real testbench will be conducted under the effect of sensor faults.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Phuc Ngoc Nguyen	✓		✓				✓			✓	✓			✓
Dinh Tu Duong	✓			✓	✓	✓		✓	✓				✓	
Hung Cuong Ta		✓				✓		✓		✓				
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Ho Vinh Pham			✓	✓	✓					✓			✓	
Huu Thang Nguyen					✓		✓		✓			✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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