©2025 Published in 11th International Symposium on Intelligent Technologies in Engineering and Science 16-18 May 2025 (ISITES2025 Diyarbakır - Turkey)

Design of Sensorless Sliding Mode Controller for Voice Coil Actuators

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Abstract

This paper proposes a sensorless control method for voice coil actuators (VCA). The position and velocity states of the VCA are estimated using a sliding mode observer (SMO). The positioning of the VCA is achieved with a sliding mode controller (SMC). A designed driver is used to control the VCA. The driver is in an H-bridge structure. Current measurement can be taken from each branch of the H-bridge. The driver's switching signals are provided by a microprocessor. Additionally, the microprocessor processes current measurements and runs the SMO/SMC algorithms. SMO is updated only with the current measured from the coil inside the VCA. Experimental studies are conducted with a constructed VCA. The critical parameters of the model used within the SMO are tuned through experiments. Experimental results show that the SMO observer can successfully perform position and velocity estimation. It is observed that the SMC, which performs positioning with the system states obtained from the estimation, can also position the VCA.

Key words: Voice Coil Actuators, Sliding Mode Observer, Sliding Mode Controller

1. Introduction

Voice coil actuators are widely used in precision positioning systems due to their high accuracy, fast response, and compact design. However, their control poses challenges such as nonlinear dynamics, external disturbances, and model uncertainties. Sliding mode control has emerged as a robust and effective control strategy for VCAs, offering advantages like disturbance rejection and insensitivity to parameter variations. This response explores various sliding mode control strategies for voice coil actuators, highlighting their design, implementation, and performance. Traditional sliding mode control is a well-established method for controlling VCAs. It involves designing a sliding surface and a control law that forces the system states to reach and stay on this surface.

Sensorless control of voice coil actuators offers several advantages, primarily by eliminating the need for physical sensors, which reduces system complexity, cost, and potential points of failure. This approach leverages the inherent properties of VCAs, such as position-dependent force and back-emf parameters, to estimate position from current measurements using sliding mode observers [1]. Sliding mode control techniques, particularly when combined with observers, enhance the robustness and accuracy of VCA positioning by effectively handling system uncertainties and disturbances. For instance, the use of complementary sliding mode control with state observers can significantly reduce tracking errors and improve transient response by suppressing uncertain factors [2]. Additionally, fuzzy sliding mode control systems, which integrate fuzzy logic to adjust control parameters in real-time, mitigate the chattering problem commonly associated with traditional SMC, thereby enhancing system stability and response speed

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[3-4]. Comparative analyses of control methods reveal that sliding mode-based approaches, such as dual-axis sliding mode control, outperform traditional PID controllers by significantly increasing closed-loop tracking bandwidth and disturbance rejection capabilities [5]. Furthermore, advanced techniques like adaptive fuzzy exponential sliding-mode control and perturbation wavelet neural sliding mode control demonstrate superior adaptability and robustness, particularly in handling nonlinearities and parameter variations in VCA systems [6-7]. These methods collectively highlight the efficacy of sliding mode observers and controllers in achieving high-precision, sensorless control of VCAs, making them a preferred choice in applications requiring precise motion control and high dynamic performance.

In this study, it is aimed to apply a sensorless controller to the VCA. An experimental VCA and its driver have been developed. A sliding mode observer is used to estimate the position and velocity of the VCA moment. SMO estimates the states only through the measurement of coil current. The driver uses a H-bridge structure to control voltage and current on the coil. Current feedback can be obtained from each bridge of the H-bridge. Thus, back EMF effect on the current measurement is reduced. Additionally, a SMO controller is also applied for position control of the VCA. Experimental studies show that VCA can be effectively positioned using only current measurement.

2. Materials and Method

VCA is an electromechanical actuator consisting of a coil and a permanent magnet. Structurally, it is similar to a DC motor. To control the direction, the direction of the current must be controlled. In this study, an actuator capable of linear motion is designed. Therefore, a movable coil and fixed magnet structure are applied. Two fixed magnets are attached to the platform in such a way that their opposite poles are aligned on the surface. A special driver is designed to drive the coil. The driver contains an integrated circuit (DRV8962) with 4 half-bridge output stages. The driver contains a microcontroller (STM32F303CC) used for running control algorithms and generating PWM signals. Fig. 1 shows the experimental VCA and driver unit.

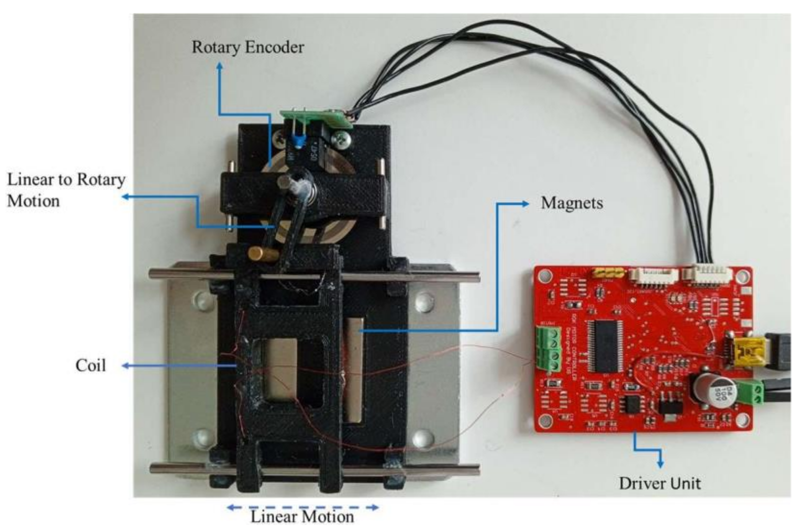

Figure 1. Experimental setup for VCA control

Although the control unit has 4 half-bridge drivers, two half-bridges are converted into a H-bridge to drive the VCA. The H-bridge structure allows for the control of current direction and the adjustment of voltage across the coil. Fig. 2 shows the VCA driver structure.

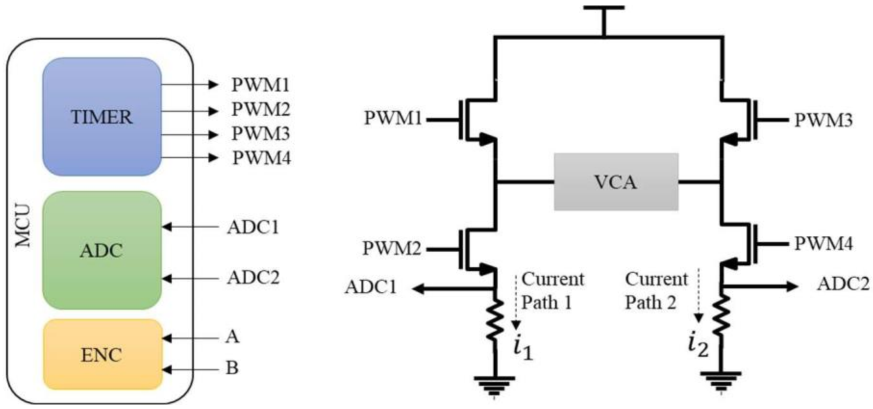

Figure 2. Driver topology

The current passing through each branch of the H-bridge can be measured. This allows to reduce back EMF effect on current measurement of the coil. The VCA has 500 turn coils with 0.2 mm diameter coated copper wire. In the experimental setup, there is one quadratic encoder sensor. The encoder is used for displacement measurement. This sensor is used only to analyze the performance of the proposed controller. A mechanical system is used to convert the linear motion of the VCA into rotational motion. In this way, displacement measurement is performed through the encoder.

2.1. VCA Model

A VAC can be modeled as a coupled electromechanical system. A common model includes both the electrical dynamics of the coil and the mechanical dynamics of the moving mass. Fig 3. shows the electro-mechanical model of the VCA. So, electrical dynamics can be modeled as

$$L_c \frac{di_c(t)}{dt} + R_c i_c(t) + K_e \dot{x}_m(t) = V_c(t) \tag{1}$$

where L_c is inductance of the coil and R_c is resistance of the coil. Back-EMF constant is denoted by K_e. The current on the coil is represented by $i_c(t)$. The applied voltage and displacement of the mass is denoted by $V_c(t)$ and $x_m(t)$, respectively. The mechanical dynamics can be model with mass and damper.

$$m\ddot{x}_m(t) + b_m \dot{x}_m(t) = K_t i_c(t) \tag{2}$$

The current of coil has two components, due to the driver topology. So, $i_c(t)$ is defined as follows.

$$i_c(t) = i_1(t) - i_2(t) \tag{3}$$

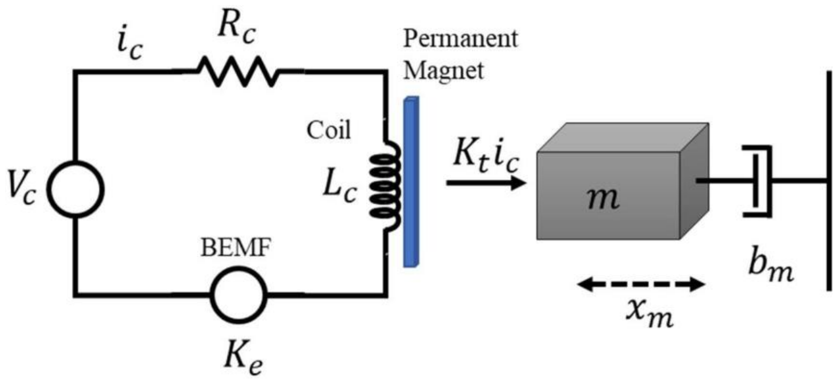

Figure 3. Electro-mechanical model of the VCA

where b_m is friction caused damping coefficient. The effect of friction is assumed as linear. Force constant of converting current to force is denoted by K_t. The mass of guided mechanism is defined by m.

2.3. Sliding Mode Observer and Sliding Mode Controller Design

VCA is generally used for the positioning of precise optical/mechanical systems. These types of systems require compact design. This situation limits the use of sensors. Sliding mode observer provides a solution in these situations. The internal states of the system can be observed with a SMO. If the system states are assumed to be displacement and velocity, it can be defined as $x_1 = x_m$ and $x_2 = \dot{x}_m$. The available measurement is i_c. So, a nominal model for the mechanical dynamics can be written in linear time invariant form as:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{1}{m}(K_t i - b_m x_2) \end{aligned} \tag{4}$$

A sliding mode observer is designed by adding a discontinuous term based on the measurement error. If assumed that $\hat{x}_1$ and $\hat{x}_2$ are estimated state, a typical SMO structure can define as

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + L_1 \operatorname{sign}(e) \\ \dot{\hat{x}}_2 &= \frac{1}{m}(K_t i - b_m \hat{x}_2) + L_2 \operatorname{sign}(e) \end{aligned} \tag{5}$$

where

$$e = x - \hat{x}_1 \tag{6}$$

and $L_1, L_2 > 0$ are the observer gains. The sign function is defined as

$$\mathrm{sign}(e) = \begin{cases} 1, & e > 0 \\ -1, & e < 0 \\ 0, & e = 0 \end{cases} \tag{7}$$

This discrete addition forces the dynamics of the prediction error onto a sliding surface. As a result, e converges to zero. Thus, it guarantees finite-time convergence under proper conditions. For control with SMC, it is assumed that the goal is to the position $x(t)$ track a desired trajectory $x_d(t)$. So, the tracking error can be defined as

$$e(t) = x_d(t) - x(t) \tag{8}$$

and the sliding surface is arranged as

$$s(t) = \dot{e}(t) + \lambda e(t) \tag{9}$$

where $\lambda > 0$ is a design parameter that influences the convergence rate. For the VCA, the control input is the applied voltage $V_c(t)$. The idea is to design $V_c(t)$ so that the closed-loop dynamics satisfy a reaching condition. First, compute the derivative of the sliding variable $s(t)$. For simplicity, assume that the dynamics have been expressed in terms of x and its derivatives. In practice, one would substitute the actuator dynamics into the derivative of the error.

$$\dot{s}(t) = \ddot{e}(t) + \lambda \dot{e}(t) = \ddot{x}_d(t) - \ddot{x}(t) + \lambda \dot{e}(t) \tag{10}$$

Since the mechanical dynamics are given by

$$\ddot{x}(t) = \frac{1}{m}\left(K_t i_c(t) - b_m \dot{x}(t)\right) \tag{11}$$

and recalling that the current $i_c(t)$ is controlled via the electrical dynamics, one can design an equivalent control $V_{eq}(t)$ that would ideally cancel the known dynamics, plus an additional term to robustly drive $s(t)$ to zero. So, sliding mode control law can be defined as

$$V_c(t) = V_{eq}(t) - K_d \mathrm{sat}\left(\frac{s(t)}{\phi}\right) \tag{12}$$

where $V_{eq}(t)$ is the equivalent control that cancels the nominal dynamics. Boundary layer thickness is denoted by $\phi > 0$. The gain $K_d > 0$ is chosen to overcome disturbances and uncertainties. $\mathrm{sat}(\varepsilon = \frac{s(t)}{\phi})$ is a saturation function and defined as follows.

$$\mathrm{sat}(z) = \begin{cases} 1, & \varepsilon > 1 \\ \varepsilon, & |\varepsilon| \leq 1 \\ -1, & \varepsilon < -1 \end{cases} \tag{13}$$

The equivalent control $V_{eq}(t)$ is obtained by setting $\dot{s}(t) = 0$ in the nominal system and solving for V_c. A common approach to verify the stability of sliding mode controllers is to use a Lyapunov candidate function. The candidate can be defined as

$$V_L(s) = \frac{1}{2} s^2 \tag{14}$$

Taking the derivative along the trajectories

$$\dot{V}_L(s) = s\dot{s} \tag{15}$$

and the sliding mode control law is defined as

$$\dot{s}(t) = -5\,\mathrm{sign}(s(t)) \tag{16}$$

with $5 > 0$, when the system has reached the sliding surface,

$$\dot{V}_L(s) = -5|s(t)| \leq 0 \tag{17}$$

This negative definiteness of $\dot{V}_L(s)$ ensures that the sliding variable $s(t)$ converges to zero, thereby guaranteeing that the tracking error $e(t)$ converges to zero.

4. Experiments and Results

The designed linear VCA has a maximum travel range of 26 mm. The VCA and SMO/SMC parameters are determined as shown in Table 1. All SMO/SMC algorithms are run in the microcontroller.

Table 1. Parameters

VCA		SMO/SMC	
m_c	0.052 kg	L_1	4.7
b_c	0.0016 Ns/m	L_2	1.2
K_t	0.052 (N/A)	K_d	9.86
L_c	0.00096 H	ϕ	1.0
R_c	14 Ohm	λ	5.0
K_e	0.01 V/(m/s)		

The SMO is a model-based estimator. Therefore, the accuracy of VCA's mechanical parameters and current measurement accuracy determine the observer's performance. Especially the viscous friction b_c and force constant K_t parameters can contain excessive uncertainty. This can lead to a decrease in the observer's performance. The parameters of viscous friction and force constant are tuned experimentally. Other parameters of VCA are obtained with measurement. In the experiments, 20 mm and 10 mm reference inputs are applied. Fig. 4 (a) and (b) shows the position and the velocity estimation. Fig. 4 (c) shows current measurement of the coil.

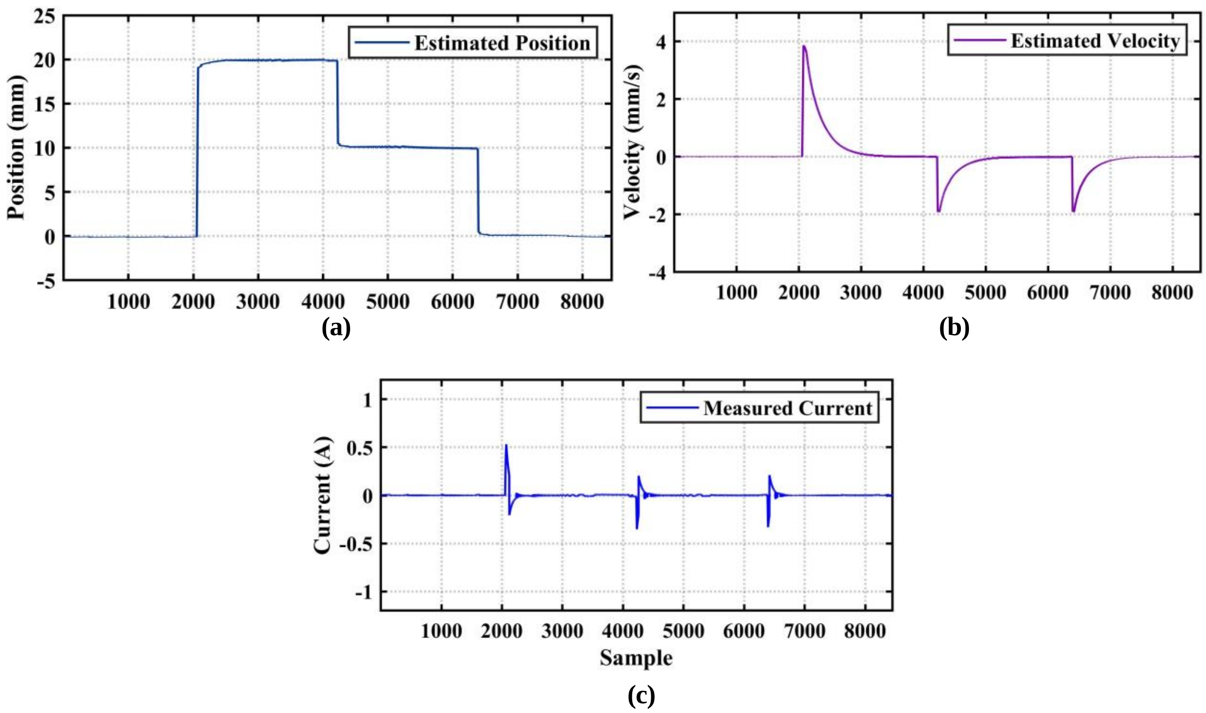

Figure 4. (a) Estimated position using SMO, **(b)** estimated velocity using SMO, **(c)** measured current of the coil.

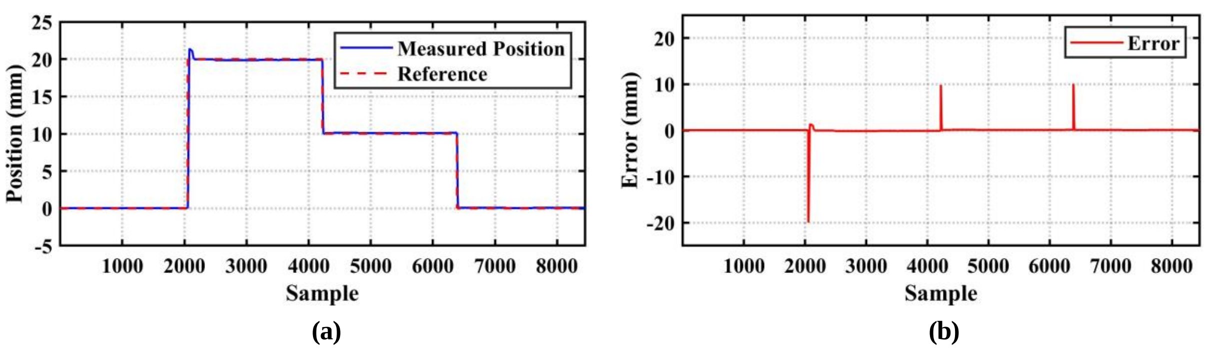

Figure 5. (a) Measured position using encoder, and **(b)** position error.

The SMO effectively performs position and velocity estimation with current feedback, as shown in Fig. 4 (a) and (b). In the microcontroller, the SMO algorithm is implemented as an iterative numerical process. Thus, it required a high refresh rate to provide state information to SMC. The refresh rate of the SMO algorithm is set as 10 KHz. The output data rate is 500 Hz. Fig. 5 shows the VCA's position response. The position information is obtained through the encoder. As seen, the VAC position response shows a satisfactory similarity to the predicted position. Additionally, SMC can respond rapidly and settle to the reference input quickly. The steady state position error is less than 0.5184 mm. There is a slight overshoot in transient response, due to parameter errors and mechanical errors.

Conclusions

In this study, the design and implementation of a sliding mode controller for a voice coil actuator, particularly used in precise optical and mechanical systems, are presented. For this purpose, an experimental linear VCA is constructed. The VCA consists of a permanent magnet and a coil. The current passing through the coil inside the VCA is controlled by a H-bridge driver. A sliding mode observer structure is applied for the position and velocity estimation of the VCA. In this way, position and velocity estimation are performed solely through current measurement. Additionally, the positioning of the VCA is achieved with a sliding mode controller. In this way, it allows the control of the VCA without the need for additional sensors. The performance of the proposed sensorless SMO controller is analyzed through experimental studies. A rotary encoder is coupled to the VCA to analyze motion performance.

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