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Original research article

Dragonfly Algorithm-Optimized Time-Varying Synergetic Control for Droplet Positioning in EWOD Systems

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ABSTRACT

This paper presents the design and implementation of a Time-Varying Synergetic Controller (TVSC) for precise droplet position control in an Electrowetting-on-Dielectric (EWOD) system. The proposed controller integrates the advantages of synergetic control (SC) and time-varying sliding mode control to enhance convergence speed while eliminating chattering in the control input. The TVSC approach utilizes macro variables derived from a time-varying sliding surface to achieve smooth and stable actuation. To optimize the controller parameters, a meta-heuristic dragonfly optimization algorithm (DA) is employed. The stability of the proposed control scheme is analytically validated using the Lyapunov stability theorem. Simulation studies are conducted to evaluate the performance of TVSC in comparison to conventional SC and Sliding Mode Control (SMC) under both translational and periodic droplet motion scenarios. The results demonstrate that TVSC achieves a faster convergence rate than SC while mitigating the chattering effect inherent in SMC. Additionally, under the influence of external disturbances, TVSC maintains superior robustness and precision in droplet positioning. This study highlights the effectiveness of TVSC in EWOD-based microfluidic applications.

Keywords: Chattering suppression; Feedback control; Microfluidic system; Nonlinear control; Optimization; Synergetic control; Sliding mode control

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1. Introduction

Micro-robotics advancement has significantly impacted various fields, including biomedical applications, lab-on-a-chip technologies, and precision material handling. Among these, electrowetting-on-dielectric (EWOD)-based microrobots have garnered substantial attention due to their ability to manipulate liquid droplets efficiently using electrically induced surface tension modulation as presented in Fig. 1. EWOD technology enables precise control over droplet motion without requiring complex mechanical actuators, making it an ideal candidate for microfluidic systems, drug delivery, and biochemical analysis [1-7].

Despite the advantages of EWOD-based microrobots, challenges persist in achieving robust and high-precision control, particularly under dynamic and uncertain environmental conditions. Traditional control strategies often struggle to compensate for nonlinearities, external disturbances, and modeling uncertainties inherent in microfluidic environments.

In this context, Sliding Mode Control (SMC) has emerged as a promising approach due to its inherent robustness and ability to handle system uncertainties and external disturbances. However, a major drawback of SMC is the chattering phenomenon in the control input, which must be mitigated to ensure smooth and efficient operation [8–10].

Synergetic Control (SC) is another effective method for controlling nonlinear dynamical systems, offering the significant advantage of chattering-free characteristics [11–17].

A key improvement in SMC is its convergence rate. The Time-Varying Sliding Mode Controller (TVSMC) provides a viable approach that allows designers to eliminate the reaching phase, thereby improving system response time [16, 18].

In TVSMC, the sliding surface is defined to pass through the initial state variable of the considered dynamical system [16, 18]. Moreover, this time-varying sliding surface is not restricted to SMC alone [16, 18] but can also be effectively applied in SC [17].

Given the advantages of the time-varying sliding surface in SMC and the chattering-free characteristic of SC, this study employs SC combined with macro variables derived from time-varying sliding surfaces to control the droplet position in the EWOD system.

In this study, the optimal selection of TVSC controller parameters for precise droplet positioning is achieved using a metaheuristic approach, specifically the Dragonfly Algorithm (DA) [16]. Originally introduced by Mirjalili [19], this algorithm mimics the swarming behavior of dragonflies, effectively balancing exploration and exploitation in search spaces. TVSC is a nonlinear control strategy that defines macro-variables to guide system behavior and ensure stability via a designed manifold. However, the effectiveness of TVSC highly depends on the optimal selection of its tuning parameters, which govern critical aspects such as convergence rate, and control effort. These parameters are often nonlinear and highly sensitive—particularly in EWOD systems, where the dynamics are inherently nonlinear. In this context, the DA offers a significant advantage by providing a global optimization approach. Unlike traditional gradient-based methods, which tend to get trapped in local minima, DA explores the solution space more effectively, increasing the likelihood of identifying globally optimal parameters for improved control performance.

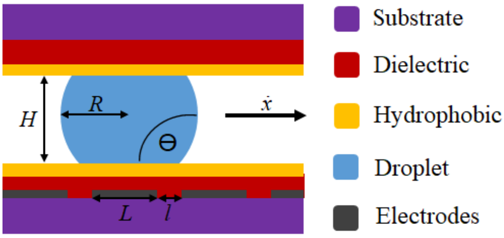

Fig. 1. Schematic diagram of the EWOD system configuration [23].

To achieve chattering avoidance in the control input and improved convergence speed, this paper addresses the following key aspects:

- Design of the TVSC for precise droplet position control in the EWOD system.
- Optimal gain tuning using a meta-heuristic approach, specifically employing the DA for controller parameter optimization.
- Performance evaluation and comparative analysis against traditional SC and SMC to demonstrate the effectiveness of the proposed approach.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive overview of EWOD-based microrobot modeling. Section 3 details the design and formulation of the proposed control strategy. Section 4 presents simulation results along with performance analysis. Finally, Section 5 concludes the paper and discusses potential future research directions.

2. Mathematical Modelling

2.1 Equation of motion

The motion of a microdroplet in an electrowetting-on-dielectric (EWOD) system can be modeled using a lumped mass approach, accounting for both driving and resistive forces [20–22]. In this mathematical representation, the droplet is treated as a rigid body in motion, subject to the combined effects of the driving force, which is the minimum force required to initiate movement, and resistive forces that oppose its motion. The system parameters are detailed in the Nomenclature section.

Based on Newton's laws of motion, the equation governing the droplet's dynamics can be expressed as follows:

$$m\frac{d^2x}{dt^2} = F_{dr}-F_{thresh}-F_c-F_d-F_f, \quad (2.1)$$

where the drag force exerted by the surrounding filler fluid (F_f) becomes negligible when the fluid is air [22]. The frictional force exerted by the contact line on the droplet (F_c) can be expressed using the following equation:

$$F_c = \varsigma\dot{x}^n(4\pi R). \quad (2.2)$$

Eq. (2.2) is expressed as a function of velocity ($\dot{x}$) and includes an exponential term (n) with a power ranging from 0 to 2 [20–22]. The resistive force resulting from the droplet's internal viscosity (F_d) can be formulated as:

$$F_d = \left(\frac{6\mu_d\dot{x}}{H}\right)(2\pi R^2). \quad (2.3)$$

Eq. (2.3) demonstrates that this force, which opposes the droplet's motion in the EWOD system, depends on velocity ($\dot{x}$), as well as the fluid properties and dimensions of the droplet.

Furthermore, the total force acting on the droplet and hence its motion depends significantly on the droplet's electrical properties, including conductivity and permittivity, which influence the electrostatic actuation in the EWOD system [20].

2.2 State space representation

To design the control law, the state-space representation of the EWOD system must first be formulated. In this system, the state variables are the droplet's displacement and velocity. Based on Eqs. (2.1)-(2.3), the system exhibits nonlinear behavior. Defining the state vector such that its components represent the droplet's displacement (x) and velocity ($\dot{x}$) provides a structured representation of the system dynamics, which is presented as follows:

$$\bar{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} x & \dot{x} \end{bmatrix}^T. \tag{2.4}$$

The state-space representation of the EWOD system in Eq. (2.1), with the driving force represented as the control input $u(t)$, can be reformulated as follows [9, 10]:

$$\dot{x}_1 = x_2, \quad \dot{x}_2 = f(\bar{x} + \frac{1}{m}u(t), \tag{2.5}$$

where $f(\bar{x})$ is a nonlinear smooth function:

$$f(\bar{x}) = \frac{1}{m}[-\left(\frac{6\mu_d x_2}{H}\right)(2\pi R^2) - \zeta x_2^n(4\pi R) + F_{thresh}]. \tag{2.6}$$

3. Controller Design

3.1 Control objective equations

The control objective is to precisely move the droplet from one electrode to a complete stop at an adjacent target electrode. The difference between the droplet's position (x_1) and the desired target position (x_{1r}) is represented as a dynamic error, which can be expressed as follows:

$$e_1(t) = x_1 - x_{1r}. \tag{3.1}$$

Therefore, the controller must be designed to ensure that the error in Eq. (3.1) approaches zero as time progresses.

3.2 Synergetic controller designs

Based on Chen and Huang [18], the first step is to select a set of macro variables that ensure the achievement of the control objective. These macro variables are derived from the switching or sliding surface, expressed as follows:

$$\Psi = e_2 + c_1 e_1 + a\exp(-bt), \tag{3.2}$$

parameters a, b and c_1 are design variables that influence the convergence of the control system. The values of b and c_1 are positive real numbers, while the value of a is determined to satisfy the condition of $P\Psi(0) = 0$. Consequently, $a = -e_2(0) - c_1 e_1(0)$ [18].

Second, the dynamic evolution of the selected macro variable in Eq. (3.2) is defined as follows [11–17]:

$$\dot{\Psi} + \lambda_1 \Psi = 0, \tag{3.3}$$

where $\lambda_1 > 0$ is the coefficients of the derivative and integral of the macro variable in Eq. (3.3) respectively. These coefficients are also design parameters.

Finally, the control input $u(t)$ is synthesized from the dynamic evolution in Eq. (3.3), based on the macro variable in Eq. (3.1) and the dynamic system of EWOD in Eq. (2.5), as follows:

$$[\dot{e}_2 + c_1\dot{e}_1 + a(-b)\exp(-bt)] + W = 0, \tag{3.4}$$

where $W = \lambda_1\Psi$. Then, substituting the dynamics from Eq. (2.5) yields:

$$[f(\bar{x} + \frac{1}{m}u - \ddot{x}_{1r} + c_1 e_2 - ab\exp(-bt)] + W = 0, \tag{3.5}$$

where $\ddot{x}_{1r}$ is the second-order derivative of the reference signal, representing the reference acceleration signal.

Then,

$$u = m\{-W - [f(\bar{x} - \ddot{x}_{1r} + c_1 e_2 - ab\exp(-bt)]\}. \tag{3.6}$$

3.3 Proof of stability

The stability proof can be established as follows. Define the Lyapunov function in terms of Ψ as

$$V = 0.5\psi^2. \tag{3.7}$$

The derivative of V is determined as

$$\begin{aligned} \dot{V} &= \Psi\dot{\Psi} \\ &= \Psi[f(\bar{x}) + \frac{1}{m}u - \ddot{x}_{1r} \\ &+ c_1 e_2 - ab\exp(-bt)]. \end{aligned} \tag{3.8}$$

Substituting Eq. (2.5) into Eq. (3.8) yields:

$$\begin{aligned} \dot{V} &= \Psi[f(\bar{x} + \frac{1}{m}u - \ddot{x}_{1r} \\ &+ c_1 e_2 - ab\exp(-bt)]. \end{aligned} \tag{3.9}$$

Then, substituting the control input into Eq. (3.9) yields:

$$\begin{aligned} \dot{V} &= \Psi(f(\bar{x}) + \frac{1}{m}m\{-W \\ &- [f(\bar{x}) - \ddot{x}_{1r} + c_1 e_2 - ab\exp(-bt)]\} \\ &- \ddot{x}_{1r} + c_1 e_2 - ab\exp(-bt)]) \\ &= \Psi(\lambda_1\Psi) = \lambda_1\Psi^2. \end{aligned} \tag{3.10}$$

According to [11–17], it is evident from Eq. (3.10) that $\dot{V} \leq 0$. Thus, the control system is proven to be stable under the designed time-varying synergetic control.

3.4 Optimization of controller parameters using the dragonfly algorithm

To determine the optimal set of controller parameters while minimizing a given cost function, the Dragonfly Algorithm (DA), a metaheuristic optimization technique, was employed. Fig. 2 illustrates the workflow for optimizing controller parameters in the EWOD system using the DA in MATLAB. The optimization process consists of the following steps:

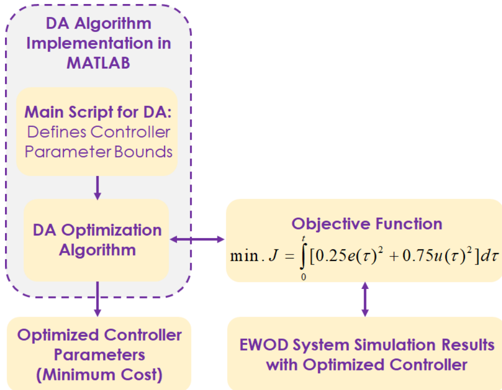

Fig. 2. Optimization framework for controller parameter tuning using the dragonfly algorithm.

- The main script defines the upper and lower bounds for the controller parameters, establishing constraints for the optimization process.
- The DA optimization algorithm searches for the optimal controller parameters by minimizing a defined cost function.
- The objective function is designed to minimize a combination of tracking error and control effort.
- After executing the optimization process, the optimal set of controller parameters is determined based on the minimum cost function value.

4. Simulation Results and Discussions

The simulation of the control system using the designed TVSC is conducted to assess its effectiveness in the EWOD system. To evaluate its performance, the simulation results are compared against those of other control methods, providing a comprehensive analysis of the designed controller's effectiveness.

4.1 Simulation example

In this study, the mathematical model of the closed EWOD system, as described in [20, 22], is used as a simulation example. The system parameters and their corresponding references are listed in Table 1.

Table 1. Parameters of the electrowetting microrobot.

Parameters	Value (Units)	References
F_{thres}	8\times 10^{-6} (N)	[22]
H	300\times 10^{-6} (m)	[20]
l	100\times 10^{-6} (m)	[22]
L	1600\times 10^{-6} (m)	-
m	7.7863\times 10^{-7} (kg)	[2]
n	2	[20]
R	8.8\times 10^{-4} (m)	[20]
θ	110°	[22]
μ_d	1.01\times 10^{-3} (Pa.s)	[20]
ρ_d	998 (kg/m^3)	[20]
ς	0.08 (Ns/m^2)	[22]

The controller parameters for the designed TVSC are defined as follows: $a = -c_1e_1(0) - e_2(0), b, c_1$, and λ_1. To ensure optimal performance, the values of b, c_1, and λ are optimally selected using the DA algorithm. The DA algorithm, implemented in MATLAB and originally presented by Mirjalili [19] has been utilized and modified to fine-tune these controller parameters. The upper and lower bounds for each parameter are defined as $0.005 \leq b \leq 1000, 5 \leq c_1 \leq 15$, and $1.05 \leq \lambda_1 \leq 2$. The upper bounds of the controller parameters are determined based on the desired approximate settling time ($t_s \leq 0.5$ seconds). To ensure sufficient flexibility during optimization, the lower bounds are set to values greater than zero, but kept relatively small compared to the corresponding upper bounds. Notably, the optimal values of the controller parameters are found to occur at the boundaries of the defined parameter range, which are $b = 1000, c_1 = 15$ and $\lambda_1 = 1.05$.

The droplet starts with an initial displacement of $x(0) = 0\ m$ and an initial velocity of $\dot{x}(0) = 0\ m/s$. The simulation runs from $t_0 = 0\ s$ to $t_f = 4\ s$ with a time increment of $\Delta t = 0.001\ s$.

4.2 Simulation results

To illustrate the performance of the designed control system (TVSC) and its enhanced convergence rate, the simulation results of the conventional synergetic control (SC) are used as a benchmark. The conventional synergetic control (SC) is defined as follows:

$$u = m\{-\lambda_1\psi - [f(\bar{x}) - \ddot{x}_{1r} + c_1e_2]\}, \quad (4.1)$$

where $\psi = c_1e_1 + e_2$. An important application of electrowetting systems is in lab-on-a-chip technology. Within these systems, droplets undergo various types of motion to perform essential microfluidic operations such as heating, transporting, splitting, merging, and mixing. Among these, translational motion is employed to transfer droplets between functional stations on the chip, facilitating sequential processing steps. In contrast, periodic motion is particularly effective for droplet mixing, as it promotes internal circulation and accelerates the homogenization of content [1, 2, 23].

Based on these droplet operations, this work presents two simulations corresponding to translational and periodic motions. The simulations are governed by two distinct reference signals:

i Translational motion, modeled by a step reference signal defined as $x_{1r} = L + l$, representing the steady displacement of a droplet across the substrate; and

ii Periodic motion, modeled by a sinusoidal reference signal $x_{1r} = (L+l)sin(\omega t)$, representing oscillatory motion intended to enhance internal mixing within the droplet where $\omega = 22\pi$ rad/s [23].

As presented in Fig. 3, the time response of displacement and velocity for the control system under the designed TVSC are plotted and compared with those of the conventional SC during translational motion. Additionally, the control input signals for both control methods are presented in Fig. 4. Both the designed TVSC and the conventional SC effectively control droplet motion, enabling the droplet to accurately reach the target position or track the desired reference signal (x_{1r}) without inducing chattering in the control input signal. However, the time responses of the designed TVSC exhibit a higher convergence rate compared to those of the conventional SC, demonstrating its improved performance.

Under identical controller parameters, the simulation of the controlled EWOD system using both the TVSC and SC methods was extended to the case of a sinusoidal reference signal—representing the periodic motion of the droplet—to demonstrate the improved convergence rate of the TVSC relative to the SC, following the methodology in [23]. The time responses corresponding to the sinusoidal reference signal are shown in Fig. 5, while the associated control inputs are illustrated in Fig. 6. The results indicate that the droplet displacement under the TVSC closely follows the sinusoidal reference and achieves a higher convergence rate than that of the SC. Furthermore, the control inputs generated by both the TVSC and SC methods are free from chattering.

For a more detailed analysis of the undesirable chattering phenomenon in the

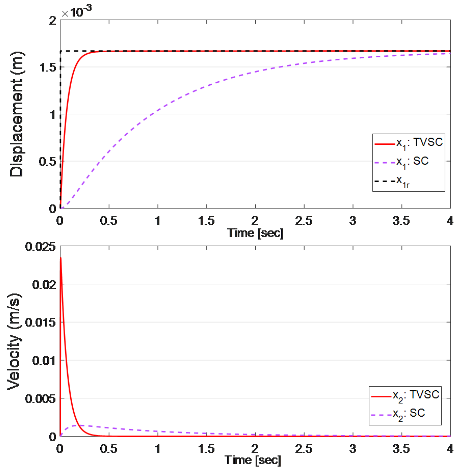

Fig. 3. Time responses of displacement and velocity for the designed TVSC, compared to the conventional SC during translational motion.

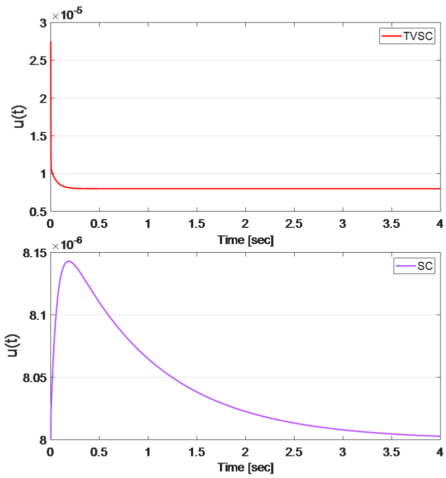

Fig. 4. Control inputs of the designed TVSC and the conventional SC during translational motion.

control input caused by external disturbances in the designed TVSC, the conventional sliding mode control (SMC), where chattering typically occurs, is used as a benchmark and defined as follows:

$$u = m\{-\lambda_1 sign(s) - [f(\bar{x}) - \ddot{x}_{1r} + c_1 e_2]\}, \quad (4.2)$$

where $s = c_1 e_1 + e_2$.

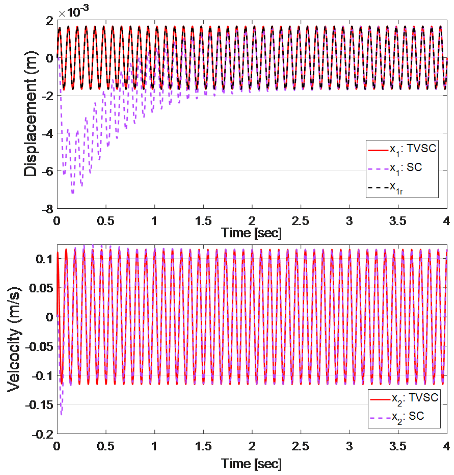

Fig. 5. Time responses of displacement and velocity for the designed TVSC, compared to the conventional SC during periodic motion.

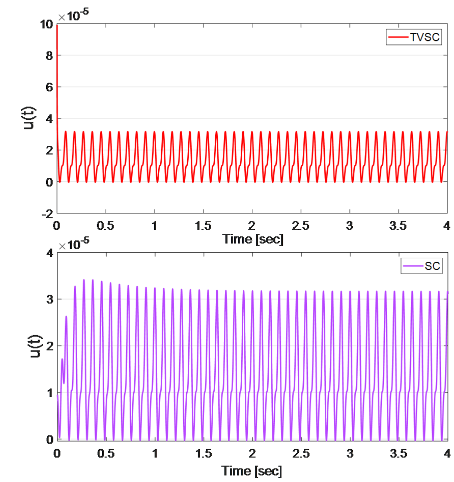

Fig. 6. Control inputs of the designed TVSC and the conventional SC during periodic motion.

The disturbance is defined as

$$d(t) = \begin{cases} A_d sin(\omega_d t) & \text{for } t_{di} \leq t \leq t_{df} \\ 0 & \text{otherwise} \end{cases}, \tag{4.3}$$

where $A_d = 2.5 \times 10^{-2}, \omega_d = 150\pi, t_{di} = 0.2s$, and $t_{df} = 0.7s$.

During the translational motion of the droplet, Fig. 7 illustrates the time re-

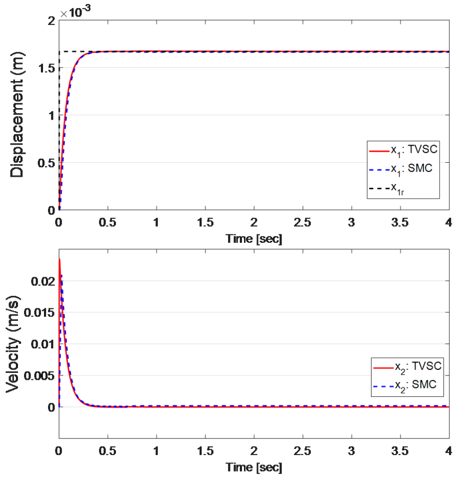

Fig. 7. Time responses of displacement and velocity for the designed TVSC, compared to the conventional SMC during translational motion.

sponses of displacement and velocity for the designed TVSC, compared to those of SMC, while Fig. 8 presents the control input signals for both methods. Despite disturbances, the designed TVSC effectively guides the droplet to the target position, similar to the SMC. However, the TVSC achieves a faster convergence rate while eliminating chattering in the control input. In contrast, the control input of the SMC exhibits noticeable chattering, particularly during the time interval from 0.2 to 0.7 seconds—a phenomenon not observed in the TVSC response.

Additionally, the simulation of the controlled EWOD system under external disturbance was conducted for both TVSC and SMC methods using a sinusoidal reference signal, representing the periodic motion of the droplet. This was performed in the same manner as for the step reference case. The corresponding time responses and control inputs are presented in Fig. 9 and Fig. 10, respectively. As shown in Fig. 9, the TVSC successfully tracks the sinusoidal reference signal, comparable to the

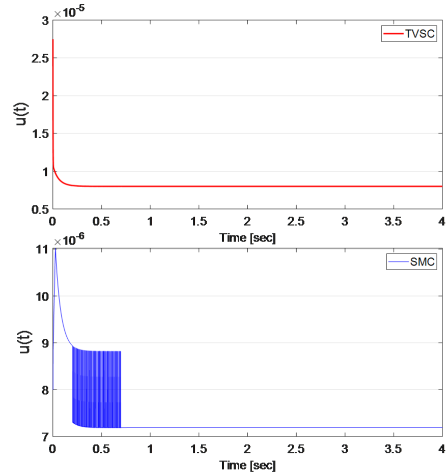

Fig. 8. Control inputs of the designed TVSC and the conventional SMC during translational motion.

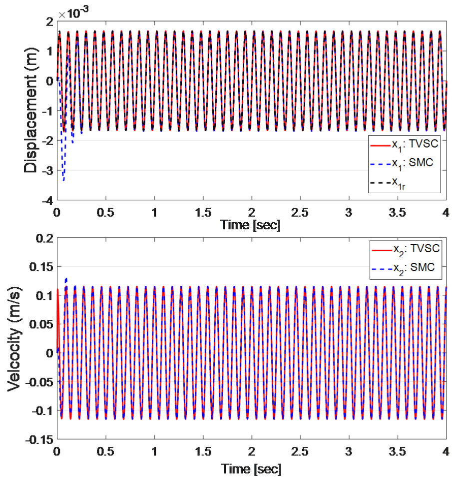

Fig. 9. Time responses of displacement and velocity for the designed TVSC, compared to the conventional SMC during periodic motion.

performance of the SMC. However, as illustrated in Fig. 10, the control input of the TVSC maintains a chattering-free characteristic, whereas noticeable chattering is observed in the control input of the SMC during the time interval from 0.2 to 0.7 seconds.

In summary, the simulation results demonstrate the effectiveness of the designed synergetic controller, which utilizes a macro variable specified based on a selected time-varying sliding surface, in controlling droplet motion. Compared to conventional SC, TVSC achieves a higher convergence rate while maintaining a smooth, chattering-free control input. Furthermore, in the presence of disturbances, TVSC performs similarly to SMC in guiding the droplet to the target position but offers the added advantage of eliminating chattering in the control input.

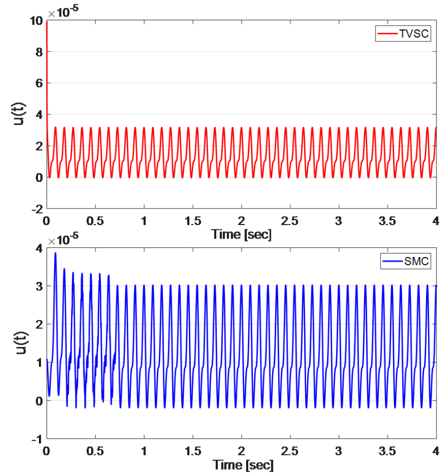

Fig. 10. Control inputs of the designed TVSC and the conventional SMC during periodic motion.

5. Conclusion

This paper presented the design and implementation of a time-varying synergetic controller (TVSC) for precise droplet position control in an electrowetting-on-dielectric (EWOD) system. The proposed control strategy was developed using a macro variable based on a selected time-varying sliding surface to enhance system performance. The stability of the control system was analytically verified using the Lyapunov stability theorem. In this study, the dragonfly algorithm (DA), a meta-heuristic optimization technique, is utilized for the optimal tuning of controller parameters. The effectiveness of the designed controller was assessed through simulation studies, comparing its performance against conventional synergetic control (SC) and sliding mode control (SMC) under both translational and periodic droplet motion scenarios. The results demonstrated that TVSC achieves a higher convergence rate than conventional SC while maintaining a smooth, chattering-free control input. Furthermore, under the influence of disturbances, TVSC successfully guided the droplet to the target position with performance comparable to SMC but with the additional advantage of eliminating chattering. This characteristic is essential for electrowetting applications, where excessive chattering can lead to instability and undesirable energy dissipation. TVSC provides a robust and efficient control solution for EWOD systems, offering enhanced stability, faster response time, and smoother actuation. Future research could focus on extending the proposed control method to multi-droplet systems, further enhancing manipulation capabilities for lab-on-a-chip and digital microfluidics applications.

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References

[1] Cho SK, Moon H, Kim CJ. Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits. J Microelectromech Syst. 2003;12(1):70-80.

[2] Berthier J. Microdrops and digital microfluidics. Norwich (NY): William Andrew; 2008.

[3] Welch ERF, Lin YY, Madison A, Fair RB. Picoliter DNA sequencing chemistry on an electrowetting-based digital microfluidic platform. Biotechnol J. 2011;6(2):165-76.

[4] Schaler E, Tellers M, Gerratt A, Penskiy I, Bergbreiter S. Toward fluidic microrobots using electrowetting. In: Proceedings of the 2012 IEEE International Conference on Robotics and Automation; 2012 May; Saint Paul, MN. p. 3461-6.

[5] Moon I, Kim J. Using EWOD (electrowetting-on-dielectric) actuation in a micro conveyor system. Sens Actuators A Phys. 2006;130-131:537-44.

[6] Crane NB, Onen O, Carballo J, Ni Q, Guldiken R. Fluidic assembly at the microscale: progress and prospects. Microfluid Nanofluidics. 2012;14(3-4):383-419.

[7] Braun T, et al. Contactless component handling on PCB using EWOD principles. In: Proceedings of the 2008 10th Electronics Packaging Technology Conference; 2008 Dec; Singapore. p. 186-92.

[8] Utkin V, Guldner J, Ge SS. Sliding mode control in electro-mechanical systems. 2nd ed. Boca Raton (FL): CRC Press; 2009.

[9] Slotine JJE, Li W. Applied nonlinear control. Englewood Cliffs (NJ): Prentice Hall; 1991.

[10] Liu J, Wang X. Advanced sliding mode control for mechanical systems. Beijing: Tsinghua University Press; Berlin: Springer-Verlag; 2011.

[11] Santi E, Monti A, Li D, Proddutur K, Dougal RA. Synergetic control for power electronics applications: a comparison with the sliding mode approach. J Circuits Syst Comput. 2004;13(4):737-60.

[12] Santi E, Monti A, Li D, Proddutur K, Dougal RA. Synergetic control for DC-DC boost converter: implementation options. IEEE Trans Ind Appl. 2003;39(6):1803-13.

[13] Kolesnikov AA, Mushenko AS. Applied theory of nonlinear system design: method comparison. In: Proceedings of the 2019 III International Conference on Control, Automation and Systems (CTS); 2019; St. Petersburg, Russia. p. 50-3.

[14] Kondratiev I, Santi E, Dougal R. Robust nonlinear synergetic control for m-parallel-connected DC-DC boost converters. In: Proceedings of the 2008 IEEE Power Electronics Specialists Conference (PESC); 2008; Rhodes, Greece. p. 2222-8.

[15] Liu CH, Hsiao MY. A finite time synergetic control scheme for robot manipulators. Comput Math Appl. 2012;64(5):1163-9.

[16] Boonyaprapasorn A, Kuntanapreeda S, Ngiamsunthorn PS, Kumsaen T, Sethaput T. Time-varying sliding mode controller for heat exchanger with dragonfly algorithm. Int J Electr Comput Eng. 2023;13(4):3958-68.

[17] Boonyaprapasorn A, Choopojcharoen T, Pengwang E, Natsupakpong S, Maneewarn T, Sa-Ngiamsunthorn P, Thung-od K. The design of a synergetic controller for tuberculosis epidemic system. Int J Mech Eng Robot Res. 2020;9(10):1439-46.

[18] Chen S, Huang H. Time-varying sliding mode surface control for high order affine non-linear systems. In: Proceedings of the 32nd Youth Academic Annual Conference of Chinese Association of Automation (YAC); 2017 May; Hefei, China. p. 559-65.

[19] Mirjalili S. Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems. Neural Comput Appl. 2016;27(4):1053-73.

[20] Bhattacharjee B, Najjaran H. Simulation of droplet position control in digital microfluidic systems. J Dyn Syst Meas Control. 2010;132(1):014501-1–3.

[21] Bahadur V, Garimella SV. An energy-based model for electrowetting-induced droplet actuation. J Micromech Microeng. 2006;16:1494-503.

[22] Oprins H, Vandevelde B, Baelmans M. Modeling and control of electrowetting induced droplet motion. Micromachines. 2012;3(1):150-67.

[23] Boonyaprapasorn A, Pengwang E, Maneewarn T. Applying fuzzy sliding mode control on electrowetting-on-dielectric system. In: Proceedings of the International Conference on Artificial Life and Robotics (ICAROB); 2016 Jan; Oita, Japan. vol. 21. p. 186-91.