Applying Fuzzy Sliding Mode Control on Electrowetting on Dielectric System

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Abstract

In Lab-on-a-chip (LOC) devices, an electrowetting on dielectric (EWOD) method can be performed to create, cut, mix, and transport droplets. Moreover, the micro assembly process of micro parts can be manipulated by the EWOD system. High accuracy of droplet motion in both applictions is required. Based on the simplified model, the feedback control such as sliding mode control can be applied so that the droplet motion can achieve a high accuracy performance under disturbances. However, the sliding mode control often has chattering problem. Thus, in this study, the fuzzy sliding mode control was applied to manipulate the droplet in the EWOD system. The study was conducted via simulation in MATLAB environment. The result showed that the proposed control method could provide an accurate motion control with lower chattering compared to that of classical sliding mode control.

Keywords: Electrowetting on Dielectric (EWOD), Digital microfluidic system, Sliding mode control, Fuzzy logic.

1. Introduction

The electrowetting on dielectric (EWOD) systems have drawn interests from engineers and scientists especially in two main applications; Lab-on-a-chip and micro assembly including micro robots and micro conveyors. The principle of the EWOD systems can be explained by utilizing the change in interfacial tension induced from the electrical voltage [1,2]. The droplet that is applied by the electrical voltage will have variation in geometries from the change in contact angle [1,2]. This allows the droplet to move by the pressure difference generated inside the droplet as shown in Fig.1 [1,2]. This phenomena is able to support the required operations in Lab-on-a-chip such as mixing, creating, cutting, and transporting[1,2]. Many of applications in Lab-on-a-chip can be seen from Refs. 1-5. Recently, some interesting EWOD systems have been presented, for example, Shen et al.[6] developed the digital micro fluidic system with micro heater for the single-nucleotide polymorphism (SNPs) detection. Lai et al.[7] proposed biomedical detection using EWOD system with multi electrode dot array architecture (MEDA). Moreover, transporting the small particle or a part using the droplet as a carrier can be implemented by EWOD principle[8,9]. This application also includes using EWOD as a micro actuator[10-12].

Another related area is the feedback control applying on EWOD system such as previous works in Refs. 13-18. For example, Shih et al.[18] employed the feedback control for the movement of the droplet in the EWOD system. According to Bhattacharjee and Najjaran[13,14], the droplet motion and operations in the EWOD system can be improved by applying feedback control. The possibility of using feedback control for EWOD system was also presented in Ref. 14.

Among various choices of control laws, the sliding mode control (SMC) has been applied to achieve the accuracy of the droplet motion in EWOD system[15,16]. The principle and capability of the control method can be found from the Refs. 19-21. However, one of the main drawbacks of this control method is the chattering issue[19-23]. In order to reduce this effect, the fuzzy logic can be combined with the sliding mode control as presented in Refs. 21-23. Therefore, the main focus of this study was to apply the fuzzy sliding mode control (FSMC) to the EWOD system. The control system was simulated to demonstrate the performance of the droplet motion control. Also, the simulation results of the FSMC method were compared to those of SMC method to evaluate the capability to reduce the chattering phenomena.

This paper is organized in following sections. The mathematical model of the EWOD system is presented in section 2. The controller design is demonstrated in section 3. In section 4, the simulation results and discussions are provided. Finally, the conclusion of the study is stated in section 5.

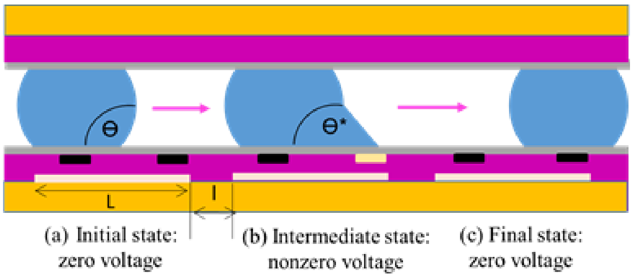


Fig. 1. Droplet movement via applying electrical field [1,17].

2. Mathematical Model of EWOD System

2.1. *Equation of motion*

The motion of the micro droplet in the EWOD system can be modeled as the one degree of freedom lumped mass model based on the Newton's law. The model is explained by previous researchers in Refs. 13-14 and 24-26. In this work, this mathematical model is used in the design procedures of this motion control.

For a mathematical model of EWOD system, the droplet is considered as the moving rigid body under the summation of driving force, threshold of driving forces, and resistive forces as shown in Fig. 2. Thus, the mathematical model describing the behavior of the droplet motion can be expressed in (1)[13,14,24-26].

$$m\frac{d^2x}{dt^2} = F_{dr} - F_{thresh} - F_d - F_c - F_f \qquad (1)$$

where the displacement and the mass of the droplet are represented by x and m respectively. The driving force (F_{dr}) is the electrical force induced from the applied voltage and the corresponding threshold (F_{thresh}) is the minimum force needed to move the droplet from the rest[1,13,14,24-27]. The terms F_d, F_f, and F_c represent resistive forces. These forces are listed and denoted as fellows: (i) F_d is the shear force acting on the droplet on top and bottom of the droplet [1,13,14,24-26]. (ii) F_f is the drag force acting on the droplet from the filler fluid [13,14,24-26]. (iii) F_c is the contact line friction force acting at the contact line on the top and bottom of the droplet[13,14,24-26]. The resistive forces can be expressed in terms of velocity of droplet ($U = \dot{x}$), fluid properties, and geometries of the droplet as shown in (2) and (3). The geometric properties of droplet related to the resistive forces are explained in the following content. (i) the radius of the droplet on the hydrophobic layer is assumed to be 5% overlapping with the length of the electrode [13,14] and denoted by a [1,13,14]., and (ii) the gap between the bottom plate and the top plate, defining the height of the droplet [13,14], is denoted by H. Relevant fluid properties are the viscosity of the droplet and the coefficient of contact line of friction. These are represented by μ_d and ς, respectively[13,14,24-26].

$$F_d = \left(\frac{6\mu_d U}{H}\right)\left(2\pi a^2\right) \qquad (2)$$

$$F_c = \varsigma U^n \left(4\pi a\right) \quad (3)$$

The exponent term (n) is in the range from 0 to 2 [13,14,24-26].

According to Ref. 24, in the case of using air as a filler fluid, the drag force (F_f) can be neglected. Readers can obtain more details of all forces in Eq. (1) – (3) from Refs. 1, 13, 14, and 24-27.

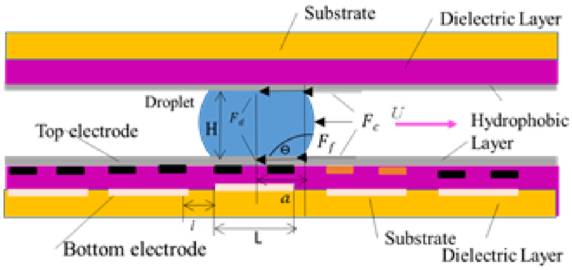


Fig 2. Moving droplet in EWOD system[13,14,17].

2.2. *State space representation*

In order to design the control law, the state space representing the EWOD system needed to be formulated. The state variables in this system are the displacement (x) and velocity ($\dot{x}$) of the droplet. Thus, the state vector of the system is defined as $\underline{x} = [x_1 \quad x_2]^T = [x \quad \dot{x}]$ [15-17], the state space representation can be formulated as (4)[15-17].

$$\left.\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f\left(\underline{x},t\right) + g(\underline{x},t)u(t) + d(t) \\ y &= x_1 \end{aligned}\right\} \quad (4)$$

where $g\left(\underline{x},t\right) = \dfrac{1}{m}$

and $f\left(\underline{x},t\right) = \dfrac{1}{m}[-\left(\dfrac{6\mu_d x_2}{H}\right)\left(2\pi a^2\right) - \zeta {x_2}^n (4\pi a)]$.

$u(t)$ is a control input representing F_{dr} and y is the output. The bounded disturbance signal is denoted as $d(t)$ and $\|d(t)\| \le M$ for $M > 0$ [15,16,21].

3. Fuzzy Sliding Mode Controller Design

The fuzzy sliding mode control (FSMC) based on an equivalent control is employed to achieve the accuracy of motion droplet in EWOD. Physically, the droplet is controlled to move from one electrode to the next one accurately along the desired periodic reference signal (x_r) under the fuzzy sliding mode control. The diagram of control can be shown in Fig. 3.

The controller design consists of two parts. The design of sliding mode controller based on an equivalent control is in section 3.1. In section 3.2, the fuzzy rules are defined for further investigations.

3.1. *Sliding mode control*

The concept of sliding mode control based on an equivalent control is based on Refs. 19-23. The procedure of sliding mode controller based on the equivalent control (from Refs. 19 and 21-23) are presented below. In this approach, the control input u is defined as shown in (5) [19,21-23].

$$u = u_{eq} + u_{sw} \quad (5)$$

where u_{eq} is an equivalent control and u_{sw} is a switching control.

The corresponding sliding surface[22, 23] or switching function[21] (s) can be expressed in term of tracking error as in (6) [19,21-23].

$$s(\underline{x},t) = c_1 e + c_2 \dot{e} \quad (6)$$

where $e = x_r - x_1$ and $\dot{e} = \dot{x}_r - x_2$. The derivative of surface function is calculated as (7) [19,21-23].

$$\begin{aligned} \dot{s}(\underline{x},t) &= c_1\dot{e} + c_2\ddot{e} \\ &= c_1\dot{e} + (\ddot{x}_r - \dot{x}_2) \end{aligned}$$

$$\dot{s}(\underline{x},t) = c_1\dot{e} + (-f(\underline{x},t) - g(\underline{x},t)u(t) + \ddot{x}_r) \quad (7)$$

When $d(t) = 0$, the equivalent control (u_{eq}) is determined by solving for $u(t)$ in (7) such that $\dot{s}(\underline{x},t) = 0$ [19,21-23].

$$c_1\dot{e} + (-f(\underline{x},t) - g(\underline{x},t)u(t) + \ddot{x}_r) = 0$$

$$u_{eq} = \frac{1}{g(\underline{x},t)}(c_1\dot{e} + \ddot{x}_r - f(\underline{x},t)) \quad (8)$$

In order to handle with the bounded disturbance $d(t)$, the switching control (u_{sw}) is designed below.

The Lyapunov function can be selected in the term of sliding surface (s) as (9) [19,21-23].

$$V = \frac{1}{2}s^2 \quad (9)$$

and the derivative is calculated as (10) [19,21-23]

$$\dot{V} = s\dot{s} \quad (10)$$

The control u_{sw} is defined as (11) [19,21-23].

$$u_{sw} = \frac{1}{g(\underline{x},t)} K \,\mathrm{sgn}(s) \quad (11)$$

where $K = \eta + M$, $\eta > 0$ [19,21-23].

The stability of the method is proved as follows. Based on the control input in (8) and (11), it can be shown that $\dot{V} = s\dot{s} \le 0$ [19,21-23] as below.

$$\dot{V} = s\dot{s}(\underline{x},t) = s[c_1\dot{e} - f(\underline{x},t) - g(\underline{x},t)(\frac{1}{g(\underline{x},t)}(c_1 e + \ddot{x}_r - f(\underline{x},t)) + \frac{1}{g(\underline{x},t)} K\,\mathrm{sgn}(s)) + \ddot{x}_r - d(t)]$$
$$= s[-K\,\mathrm{sgn}(s) - d(t)]$$
$$= -s(M+\eta)\mathrm{sgn}(s) - sd(t) = -\eta|s| \le 0. \qquad (12)$$

It is noted that the stability is satisfied by the control input (5) as $\dot{V} \le 0$ [19,21-23]. According to $f(\underline{x},t)$ and $g(\underline{x},t)$ in (4), the control EWOD system can track the reference signal accurately.

3.2. *Fuzzy rules*

In order to reduce the chattering problem caused by switching control (u_{sw}), the fuzzy rules is used to assign the value of switching gain (μ). This switching gain is depended on the magnitude of the disturbance [21,23]. When $\mu = 1$ in the case of SMC method, the control input in (5) becomes (13) for the case of FSMC [21,23].

$$u = u_{eq} + \mu u_{sw} \qquad (13)$$

In the fuzzy system, μ is a fuzzy output derived from the switching function input (s). The range of μ and s are defined to be from -1 to 1[21]. The fuzzy rules are defined for the sliding mode control in (14) as presented in Ref. 21.

$$\left.\begin{array}{l} \text{If } s = 0 \text{ , then } \mu = 0 \\ \text{If } s < 0 \text{ , then } \mu > 0 \\ \text{If } s > 0 \text{ , then } \mu > 0 \end{array}\right\} \qquad (14)$$

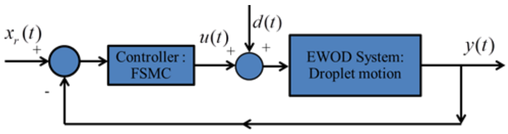


Fig 3. The Fuzzy sliding mode control applying on EWOD system [15,16].

4. Simulation Results and Discussions

The simulation was performed in MATLAB environment to evaluate the feasibility of fuzzy sliding mode control (FSMC) based on an equivalent control for the droplet motion in EWOD system. In addition, the chattering in the control input was considered. Thus, the simulation results of both FSMC and SMC methods were compared especially the chattering in the control inputs. In simulation, the Runge-Kutta method was used for integration from initial time ($t = 0$ s) to final time ($t = 0.5$ s) with the sampling time (0.00001 s).

4.1. *Simulation example*

The simulation example of the EWOD system has two groups of parameters; the fluid properties and the geometry of the component of EWOD system. All necessary parameters with numerical values are summarized in this section. The dimensions of the EWOD system are as follows. First, the gap of the top and bottom surfaces was $H = 300\times10^{-6}\,\mathrm{m}$ [13,14]. Second, the length electrode and the gap between them were $L = 1600\times10^{-6}\,\mathrm{m}$ and $l = 70\times10^{-6}\,\mathrm{m}$ as Ref. 28. The fluid properties used in simulation were as follows: (i) density of the droplet was $\rho_d = 998\ kg/m^3$ [29], (ii) the contact angle of the droplet on the hydrophobic surface was $\theta = 110^\circ$ [24], (iii) coefficient of contact line friction was $\varsigma = 0.08\ \mathrm{Ns/m^2}$ [24], (iv) the radius of the droplet, $a = 8.8\times10^{-4}\,\mathrm{m}$, defined under the overlap condition as $a = 0.5L + 0.05L$ [13,14], and (v) the value of an exponent term was $n = 2$. After the primary parameters were defined, the mass of the droplet (m) was $7.7863\times10^{-7}\,\mathrm{kg}$, that was calculated from ρ_d and a [1]. The value of threshold force was assumed as $F_{thresh} = 8\times10^{-6}\ N$ [24]. The disturbance signal was assumed to be the Gaussian function as (15) [21].

$$d(t) = Ae^{\frac{-(t-m_d)^2}{2s_d^2}} \qquad (15)$$

where $A = 3000\times10^{-6}$, $m_d = 0.15$, and $s_d = 0.02$. Most of the numerical values in this simulation were used before in our previous work [15-17]. Assuming that droplet was at rest at the initial time, the initial condition for the state variables in this simulation was defined as $x_1(0) = 0$ m and $x_2(0) = 0$ m/s [15-16].

4.2. *Sinusoidal reference signal*

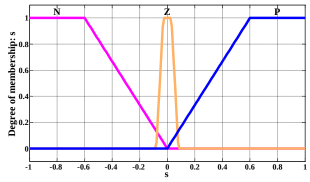
The sinusoidal function was the reference signal representing the periodic motion of the droplet travelling between two adjacent electrodes as a mixing process in Lab-on-a-chip[1,2,15].

$$x_r(t) = (L + l)\sin(\omega t) \qquad (16)$$

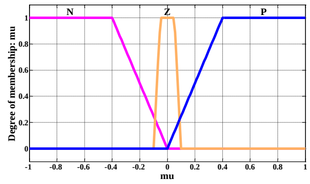
The amplitude of the signal is a distance between two adjacent electrodes, including the gap between two electrodes [15]. The frequency of the signal was assumed to be $\omega = 20\pi$ rad/s.

4.3. *Control parameter*

The control parameters consisted of constant terms in (6) and (11), which were selected as $c_1 = 50$, $c_2 = 1$ and $K = 15.6$. The parameter μ in (13) is defined by fuzzy rules. The membership function of the fuzzy system corresponding to μ and s are shown in Fig. 3(a) and 3(b) respectively. The terms of N, Z, and P are negative, zero, and positive values for s and μ in fuzzy rules[21]. Moreover, a centroid of area method was used in defuzzification.



(a)

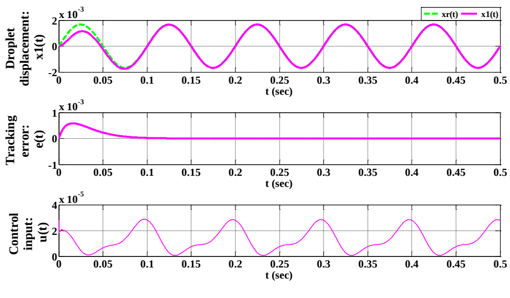


(b)

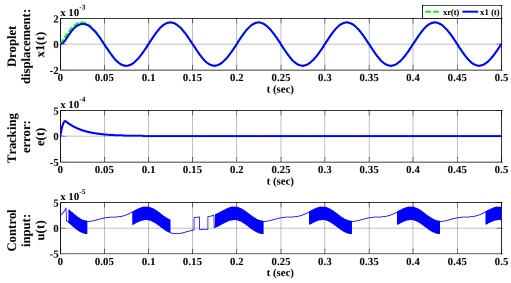
Fig. 3. Fuzzy's Rule: (a) membership function for s (b) membership function for μ.

4.4. *Results of simulation example*

The displacements of the droplet, tracking errors, and control inputs corresponding to the FSMC and SMC method based on an equivalent control are shown in Fig. 4(a) and 4(b) respectively. In Fig. 4, when employing the FSMC method, the control system could track the sinusoidal reference signal accurately as the SMC method. However, the tracking error of the FSMC method converges to zero slower than that of the SMC method. Additionally, the chattering in the control input of the FSMC method was less than that of the SMC method as shown clearly in Fig. 5.



(a)



(b)

Fig. 4. The displacement, tracking errors, and control inputs; (a) Fuzzy sliding mode control (b) Sliding mode control.

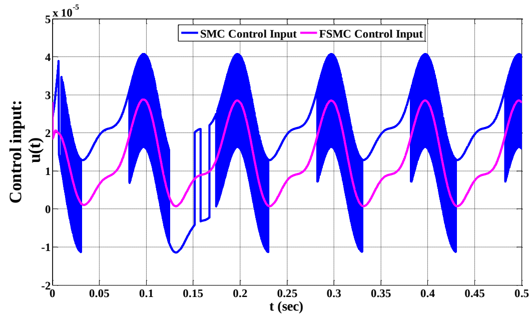


Fig. 5. Control input signal of FSMC (Pink) and SMC (Blue) methods.

5. Conclusions

This study illustrated that the FSMC method could provide a good accuracy in tracking the periodical signal under the disturbance. Thus, the droplet in the EWOD system was able to track the periodic signal accurately by using the FSMC method under the disturbance signal with lower chattering compared to that of the SMC method. The reduction of the chattering was important for this method, especially in the implementation of practical control system. Therefore, the fuzzy sliding mode control based on an equivalent control was successfully applied for the micro droplet motion in this EWOD.

6. References

1. J. Berthier, *Microdrops and Digital Microfluidics* (William Andrew, Norwich New York, 2008).
2. S. K. Cho, H. Moon and C. J. Kim, Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits, *Journal of Microelectromechanical Systems*. **12**(1), February 2003, pp. 70-80.
3. V. Srinivasan, V. K. Pamula, M. G. Pollack and R. B. Fair, Clinical diagnostics on human whole blood, plasma, serum, urine, saliva, sweat, and tears on a digital microfluidic platform, in *Proceedings of the 7th*

International Conference on Miniaturized Chemical and Biochemical Analysis Systems, Squaw Valley, California, U.S.A., October 5-8, 2003, pp. 1287-1290.

4. C. Rivet, H. Lee, A. Hirsch, S. Hamilton and H. Lu, Microfluidics for medical dianostics and biosensor, *Chemical Engineering Science* **66** (2011), pp. 1490-1507.
5. H. C. Lin, Y. J. Liu and D. J. Yao, DNA ligation using coplanar electrodes electro-wetting- ondielectric (EWOD) device, in *Proceedings of the 2009 4th IEEE International Conference on Nano/Micro Engineering and Molecular Systems (NEMS 2009)*, Shenzhen, January 5-8, 2009, pp. 358-389.
6. H-H. Shen, T-Y. Su, H-Y. Chang and D.-J. Yao, SNP detection based on temperature-controllable EWOD digital micro fluidics system, in *Proceedings of the 2012 IEEE Nanotechnology Material and Device Conference*, Hawaii, U.S.A., October16-19, 2012, pp. 92-95.
7. K. Y.-T. Lai, Y. T. Yang and C. Y. Lee, An intelligent digital microfludic processor for biochemical detection, *Journal of Signal Processing System (2015)* **78**, pp. 85-93.
8. T. Braun, K. F. Becker, M. Koch, E. Jung, J. Lienemann, J. G. Korvink, R. Kahle, J. Bauer, R. Aschenbrenner and H. Reichl, Contactless Component Handling on PCB using EWOD principles, in *Proceedings of* 2008 *10th Electronics Packaging Technology Conference, 2008 (EPTC 2008)*, Singapore, December 9-12, 2008, pp. 186-192.
9. E. Schaler, M. Tellers, A. Gerratt, I. Penskiy and S. Bergbreiter, Toward fluidic microrobots using electrowetting, in *Proceedings of 2012 IEEE International Conference on Robotics and Automation (ICRA),* Saint Paul, MN, U.S.A., May 14-18, 2013, pp. 3461–3466.
10. I. Moon and J. Kim, Using EWOD (electrowetting-on-dielectric) actuation in a micro conveyor system, *Sensor and Actuators A: Physical*, **130-131** (2006), pp. 537-544.
11. W. Satoh, H. Hosono, K. Morimoto and H. Suzuki, Micro analysis system with an integrated microfluidic system based on electrowetting, in *Proceedings of. the fourth IEEE Conference on Sensors (IEEE SENSORS 2005)*, Irvine, CA, U.S.A., October 30-November 3, 2005, pp. 37-40.
12. A. Takei, N. Binh-Khiem, E. Iwase, K. Matsumoto and I. Shimoyama, Liquid motor driven by electrowetting, in *Proceedings of IEEE 21st Conference on Micro Electro Mechanical Systems, (MEMS 2008)*, Tucson, Arizona, U.S.A., January 13-17, 2008, pp. 42-45.
13. B. Bhattacharjee and H. Najjaran, Simulation of droplet position control in digital microfluidic systems, *Journal of Dynamic Systems, Measurement, and Control* **132**(1) (2010), pp. 014501-1-014501-3.
14. B. Bhattcharrjee and H. Najjaran, Droplet position control in digital microfluidic systems, *Biomed Microdevices* **12** (2010), pp. 115-124.
15. A. Boonyaprapasorn and T. Sethaput, Design of sliding mode controller for droplet position in EWOD microfluidic system, in *Proceedings of the 2015 International Conference on Artificial Life and Robotics (ICAROB 2015)*, Oita, Japan, January 10-12, 2015, pp. 17-21.
16. A. Boonyaprapasorn, E. Pengwang, T. Maneewarn, P. Sa Ngiamsunthorn, C. Pongsomboon, W. Wechsathol and R. Silapunt, Backstepping and backstepping sliding mode controller for droplet position in electrowetting on dielectric system, in *Proceedings of 2015 15th International Conference on Control, Automation and Systems (ICCAS 2015)*, Bexco Busan, Korea, October 13-15, 2015, pp. 1457-1462.
17. A. Boonyaprapasorn, T. Maneewarn and E. Pengwang, Position control of droplet in electrowetting on dielectric system using feedback linearization, in *Proceedings of The 6th TSME International Conference on Mechanical Engineering*, Regent Cha-Am Beach Resort, Petchburi, Thailand, December 16-18, 2015, (accepted September 15th , 2015).
18. S. C. C. Shih, R. Fobel, P. Kumar and A. R. Wheeler, A feedback control system for high-fidelity digital microfluidics, in *Proceedings of 14th International Conference on Miniaturized Systems for Chemistry and Life Sciences*, Groningen, The Natherland, October 3-7, 2010, pp. 2032-2034.
19. J-J. E. Slotine and W. Li, *Applied Nonlinear Control* (Prentice Hall, New Jersey, 1991).
20. V. I. Utkin, *Sliding Modes in Control and Optimization* (Springer-Verlag, Berlin Heidelberg, 1992).
21. J. Liu and X. Wang, *Advanced Sliding Mode Control for Mechanical Systems*, (Tsinghua University Press, Beijing, and Springer-Verlag, Berlin Heidelberg, 2011).
22. C. C. Kung and C. C. Liao, Fuzzy-sliding mode controller design for tracking control of nonlinear system, in *Proceedings of the American Control Conference*, 1994, **1**, Baltimore, Maryland, U.S.A., June 29th –July 1st , 1994, pp. 180-184.
23. J.-Y., Chen, Expert SMC-based fuzzy control with genetic algorithms, *Journal of The Franklin Institute* **336** (1999), pp. 589-610.
24. H. Oprins, B. Vandevelde and M. Baelmans, Modeling and control of electrowetting induced droplet motion, *Micromachines* **3** (2012), pp. 150-167.
25. V. Bahadur and S. V. Gaimella, An energy-based model for electrowetting–induced droplet actuation, *Journal of Micromechanics and Microengineering* **16** (2006), pp. 1494-1503.
26. H. Ren, R. B. Fair, M. G., Pollack and E. J. Shaughnessy, Dynamics of electrod-wetting droplet transport, *Sensor and Actuators B.* **87** (2002), pp. 201-206.
27. J. Berthier, P. Dubois, P. Clementz, P. Claustre, C. Peponet and Y. Fouillet, Actuation potential and capillary forces in electrowetting based microsystem, *Sensor and Actuators A* **134** (2007), pp. 471-479.
28. C. Phongsomboon, Mobility control of a droplet on top of a flat plate, M.S. thesis, Dept. Mechanical Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand, 2012 (in Thai).
29. R. W. Fox, P. J. Pritchard and A. T. Mcdonald, *Introduction to Fluid Mechanics 7th edition* (John Wiley and Sons, Hoboken, NJ, 2010).