Research Article

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Machine vision-based driving and feedback scheme for digital microfluidics system

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Abstract: A digital microfluidic system based on electro-wetting-on-dielectric is a new technology for controlling microliter-sized droplets on a plane. By applying a voltage signal to an electrode, the droplets can be controlled to move, merge, and split. Due to device design, fabrication, and runtime uncertainties, feedback control schemes are necessary to ensure the reliability and accuracy of a digital microfluidic system for practical application. The premise of feedback is to obtain accurate droplet position information. Therefore, there is a strong need to develop a digital microfluidics system integrated with driving, position, and feedback functions for different areas of study. In this article, we propose a driving and feedback scheme based on machine vision for the digital microfluidics system. A series of experiments including droplet motion, merging, status detection, and self-adaption are performed to evaluate the feasibility and the reliability of the proposed scheme. The experimental results show that the proposed scheme can accurately locate multiple droplets and improve the success rate of different applications. Furthermore, the

proposed scheme provides an experimental platform for scientists who focused on the digital microfluidics system.

Keywords: digital microfluidics system, electrowetting-on-dielectric, machine vision, position, feedback

1 Introduction

A digital microfluidic (DMF) system is a new technology recently developed from the continuous microfluidic technology. The DMF system provides a means of manipulating droplets in a wide range of volumes. Each droplet can be moved, merged, and dispensed. Compared with the continuous fluid microfluidic technology, DMF has unique advantages of effectively avoiding contamination between liquids and removing dead zones, greatly reducing reagent consumption [1–3].

A DMF system controls individual droplets on a planar electrode array by using various driving mechanisms, such as temperature gradient [4], acoustic wave [5], electrostatic [6], and electrowetting-on-dielectric (EWOD) [7]. Among them, the EWOD-based DMF system has become a top research focus area due to its simple structure, easy fabrication, and strong driving forces [8,9]. The practicability of EWOD-based DMF as a lab-on-a-chip platform has also been discussed and studied. Basic operations such as creating, moving, splitting, and merging droplets have been demonstrated in the previous studies [10–12].

With EWOD driving forces, droplets are manipulated over an array of electrodes by applying electrical signals to the individual electrodes. When an electrode is energized, EWOD forces pull the droplet toward the energized electrode (shown in Figure 1). The displacement of the droplet's motion is approximately equal to the width of the electrode. The droplet transfer rate and motion path are experimentally pre-determined [13]. This driving control mechanism assumes that the droplet moved completely to the energized electrode during the precalibrated driving time before energizing the next electrode [13]. This mechanism is considered an open loop model since it is based on the precalibrated control by a fixed driver.

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Figure 1: EWOD-based droplet driving principle.

In practical experiments, device surface defects such as dust particles impede droplets from moving to adjacent energized electrodes. However, the driving control system will continue to actuate the next electrode, even when the droplet has stopped on the previous electrode. In the previous studies, the EWOD chip status was monitored manually, but it should be automated for practical applications.

Therefore, research teams have proposed few droplet position methods to monitor the droplet status. In a closed-loop EWOD chip control model, the driving control system has a detection mechanism to sense whether the droplet has completely moved to the energizing electrode before activating the next electrode [14].

Capacitive sensing is the commonly used and mature scheme for locating droplets on EWOD devices [15]. Multiple droplets can be successfully located, and uniform size droplets are generated by using this method [16–18]. Furthermore, the detection of multiple droplets on a single EWOD device using capacitive-to-digital converter (CDC) integrated circuit (IC) has been demonstrated by Li *et al.* [19]. This method is easy to implement and of low cost, but it is time consuming. Especially for complex EWOD devices, much system memory is required to store many capacitance values in memory for the analysis. In addition, it is difficult to use in EWOD devices with different electrode sizes.

The previous studies proposed a droplet position scheme based on image techniques [20–22]. This method is implemented by an image processing algorithm, which extracts the droplet parameter information, including droplet position [23]. Compared with capacitive-based sensing methods, its advantages are high efficiency and accuracy. However, machine vision-based methods are costly and difficult to develop. Most studies do not include the priority analysis or a driving parameter feedback model. Recently, Jain and Patrikar demonstrated a

low-cost portable dynamic droplet sensing system for DMF system applications [24]. This proposed system can monitor the droplet position by using electrical and optical methods. Moreover, a feedback mechanism is also implemented in this system.

In this study, we propose a driving and feedback scheme based on machine vision for DMF applications. A priority adjustment strategy for driving parameters is implemented in the proposed scheme. This scheme can measure droplet parameters including position, velocity, and volume. Furthermore, the EWOD chip status can be obtained by a feedback mechanism. The proposed system is composed of a high-resolution camera, a computer with a graphical image analysis system, and a portable driving control system. It can achieve precise control of multiple droplets without adding any physical sensors to the EWOD device.

We applied this scheme to (1) show droplet control: shuttling, (2) control a chemical reaction: two droplets were merged, (3) monitor the EWOD chip status, and (4) demonstrate its feasibility and reliability in stress testing. Furthermore, we present the design details for the proposed system and believe that this system can be useful for researchers studying different chemical and biomedical applications.

2 Methods and materials

2.1 EWOD device structure and materials

The EWOD device comprises an electrode array of photolithography patterned metal (indium tin oxide) on a glass substrate with a ground plane (indium tin oxide on glass)

connected parallel to it. The electrode array and the ground plane are separated by a gasket of known thickness (H). Some individual droplets are contained between the electrode array and the ground plane. To reduce friction, silicone oil (mass fraction: 10%) was used as the lubricant surrounding the droplets in previous studies.

A hydrophobic insulating layer is spin coated to insulate the droplets from the electrode array. In our study, Teflon AF 1600 (800 nm) is used as a dielectric as well as a hydrophobic layer in the EWOD device. Note that the Teflon AF 1600 is a biocompatible polymer with an average static contact angle of 116° . Its dielectric constant is approximately 2.4. This characteristic is conducive to various droplet operations [25]. The top view of a closed EWOD chip is shown in Figure 2(a). It consists of 10 ($3\text{ mm} \times 3\text{ mm}$) square electrodes with a $50\text{ }\mu\text{m}$ separation between adjacent electrodes. The height between the upper plate and the lower plate is approximately 1.5 mm. To ensure the stability of the EWOD chip and the reliability of the circuit connection, we designed a printed circuit board (PCB) foil as the interface between the EWOD chip and the external driver circuit. Each electrode is connected to an external driving chip interface by a separate electrical wire. The spacing between the adjacent electrical wires is 1 mm. Detailed parameters and dimensions of the PCB foil are shown in Figure 2(b).

2.2 Machine vision-based driving and feedback scheme

Figure 3 shows a schematic illustration of the machine vision-based DMF driving and feedback scheme in a double-plate EWOD chip configuration. The four major components include the double-plate EWOD chip, a high-

resolution camera, a computer with a graphical image analysis system, and the driving control system.

There are four key modules in the design of the EWOD chip machine vision-based driving and feedback scheme: image acquisition, image processing and recognition, chip status analysis, and feedback and driving. The original EWOD chip image, including droplets, captured by the camera must be processed through an image algorithm. The complete image processing and the analysis solution are shown in Figure 4. The background of the EWOD chip and the droplet shapes have obvious differences. Background subtraction and droplet extraction are the two main algorithms used in our study to capture the real-time position of droplets on the EWOD chip.

First, the K-nearest neighbor (KNN) background model of the original image is built by the image analysis system. Then, we use morphology to analyze the processed images and set appropriate “expansion” parameters. We also develop a median-based Gaussian weighted filter (MGWF) that is effective for image edge filtering. To eliminate salt-and-pepper noise, an improved adaptive filtering (IAMF) algorithm is used in this study. Finally, the positions of droplets are recognized by a circular edge detection algorithm.

The proposed driving control system is programmed to control a series of droplet actuations and acquire image information from the image analysis system to manage the control logic for the sequential operations. Different droplet operations (e.g., move, dispense, merge) can be automatically controlled based on the recognition and feedback.

2.3 Driving control system

The EWOD device driving control system architecture diagram is shown in Figure 5. We use an embedded

Figure 2: (a) Top view of the closed EWOD chip. (b) Detailed parameters and dimensions of the PCB foil.

Figure 3: A schematic illustration of the EWOD chip machine vision-based driving and feedback scheme.

microcontroller (STM32F7) as the control core of the driving control system. Its frequency can reach 180 MHz, and it has abundant communication interfaces (i.e., SPI, I²C, and a serial port). To actuate the droplet from one electrode to another electrode, a high voltage signal is necessary. Most previous studies used a “boost converter + relay” as the voltage output module. However, the problem with this design is that the voltage rise time is high (e.g., 200–500 ms). To avoid this problem, an SSD1627 chip is used as a voltage output module in the proposed driving control system. It has 98 I/O ports, each of which can work together or independently and output 18–40 V of driving voltage [26]. These characteristics can meet the driving requirements of EWOD devices very well. All the real-time data are stored in an external electrically erasable programmable read-only memory (EEPROM; 32 kB, M95320-R, STMicroelectronics). The serial port is used as a data exchange interface between the image analysis system and the driving control system. The proposed driving control system has the advantages of easy fabrication, portability, and a high level of integration.

2.4 Feedback model for droplet actuation

As described earlier, the real-time positions of droplets on the EWOD chip can be obtained by the proposed location system. Furthermore, the droplet position data are provided to the driving control system as feedback.

In this study, we present a priority adjustment strategy for driving parameters based on feedback (Table 1). The criterion of the proposed feedback model is to improve DMF application efficiency without affecting the EWOD chip stability as much as possible.

For the proposed system, users must enter values for parameters required to actuate the droplets on the device before the system starts. These parameters mainly include electrode radius, droplet radius (i.e., one and a half of the electrode size), initial single driving time (i.e., time duration for one pulse), incremental time (i.e., time duration for one adjustment), initial driving voltage (i.e., initial voltage applied to the electrode), incremental voltage, initial electrode, and destination electrode.

Figure 4: The complete image processing and analysis solution.

To ensure the reliability and safety of the EWOD chip, the highest driving parameter adjustment priority is given to the single driving time. Generally, for most DMF applications, the single drive time is less than 2,000 ms. A change in the driving time will not affect the EWOD chip reliability.

Droplet operations (e.g., moving or splitting) are highly dependent on driving voltage. Due to various defects on the electrode surface, a larger driving voltage is beneficial to overcome the resistance to droplet movement. However, excessive driving voltage may cause degradation of the dielectric layer, reducing the lifetime of EWOD device. Consequently, it takes second priority. It should be noted that the incremental voltage should not be set too large in most applications. In our study, it was set to 2 V.

In this study, we first proposed the droplet motion path as a modifiable parameter in the feedback model. The droplet motion path has the lowest priority. Generally, the default droplet motion path is the optimal path. Some experiments revealed that there can be droplet motion failure even if the driving voltage and time are sufficiently large. In this case, the driving control system must adjust

Figure 5: Driving control system architecture diagram.

Table 1: Priority adjustment strategy for driving parameters based on feedback

Driving parameters	Priority
Single driving time	1 (top)
Driving voltage	2
Droplet motion path	3

the droplet motion path. For soluble droplets, the motion path recalculation for a particular droplet must consider the motion paths of all droplets (i.e., at least two electrodes should separate the droplets). This requires that the control system not only have accurate droplet positioning capability but also have powerful calculation and analysis ability. In our software, the shortest path method is used to recalculate the new droplet motion path.

The feedback control pseudo code is presented in Table 2. The software used in this article is written in the standard C/C++ language. By using the modular design, the efficiency, expansibility, and maintainability of the software are improved. The driving voltage and time are accumulated based on cyclic iteration in the proposed system. Because the voltage rise time of the SSD1627 chip is approximately 10 ms, the modification of driving parameters for droplet control can occur quickly.

Table 2: Feedback control pseudo code

Main program ():	Adjustment of driving parameters ():
System_Start ();	Voltage = default
System_Init ();	Time = default
N = 0;	Voltage_ increase = default
While (1)	Time_ increase = default
{	Voltage_Max = default
Electrode_ Activation(N);	Time_Max = default
P = Check_Droplet_Postition ();	If (Time < Time_Max)
If (P == fail)	{
{	Time = Time + Time_
	increase;
	Return;
Adjustment of driving	
parameters ();	
Electrode_ Activation(N);	}
}	If (V < Voltage_Max)
Else (P == success)	{
{	Voltage = Voltage + Voltage_
	increase;
N = N + 1;	Return;
}	}
}	Droplet_Motion_Path ();
	Return;
	}

Ethical approval: The conducted research is not related to either human or animal use.

3 Results and discussion

3.1 Droplet location experiment

The image analysis system is programmed based on the OpenCV library, which is used to develop and verify the proposed detection and recognition scheme in the Visual Studio (VS) 2015 environment.

First, we set up a droplet location experiment to demonstrate the proposed system's algorithm flow. To detect the droplet position, four operations were executed every 300 ms to judge whether the droplet had dispensed from the reservoir electrode or transferred successfully over the activated electrode. The algorithm flow of the machine vision-based driving and the feedback system is shown in Figure 6.

Step 1: The image analysis system acquires an original frame captured by the high-resolution camera. Step 2: The image analysis system calculates a difference image for the droplet by subtracting a reference image. Step 3: The image analysis system binarizes the difference image using a series of image algorithms. Step 4: The image system uses a Hough transform function to detect droplets on electrodes. Step 5: The image analysis system returns a successful or unsuccessful result to the driving control system. A failed droplet motion will trigger driving parameter adjustment (as presented in

Figure 6: Algorithm flow of the machine vision-based driving and feedback system. (a) Original image of EWOD device. (b) Image graying and background extraction. (c) Image binaryzation. (d) Droplet location.

Figure 7: The comparison results of the two droplet motion methods. (a) Success rate of droplets shuttled under different driving schemes. (b) The time of droplet movements under different control schemes.

Table 1, there are three priorities) until the motion is successful. If the droplet successfully moved to the target electrode, it will be driven to the next electrode based on the default droplet path. These procedures are designed to set up a closed loop, so that droplet detection and driving are executed continuously and simultaneously.

In this instance, a droplet was stationary at the x electrode. The driving control system activated the y electrode. An original frame was captured by the high-resolution camera, as shown in Figure 6(a). A grayscale frame was obtained from the original frame (Figure 6(b)). In our study, a reference image of the EWOD chip was acquired without visible droplets on any of the electrodes. This reference image is acquired for droplet edge detection and droplet position subtraction techniques. Furthermore, a binary frame is created using image-processing algorithms. From this frame, a Hough transform function can be used to detect circles (droplets), as shown in Figure 6(d).

After sensing the droplet's position, the feedback model is applied to ensure that droplets can reach the target electrode smoothly. As described earlier, the system will first adjust the single driving time if the droplet motion has failed.

3.2 Droplet motion experiment: shuttling

Surface defects on a hydrophobic layer may cause unsteady motion. If droplet motion is unexpectedly slowed, sequential electrode activation without feedback will result in an out-of-control droplet. In this section, droplet shuttling was selected as a verification experiment for demonstrating the

machine vision-based driving and feedback scheme. The purpose of this experiment is to demonstrate the effect of the proposed scheme on the success rate of continuous droplet motion. Shuttling means that the droplet moves back and forth frequently in the EWOD chip. In this experiment, a droplet shuttled in a linear EWOD chip consisting of eight electrodes. The electrode diameter is 5 mm, and their spacing is 20 μm . The number of activated electrodes ranges from 1 to 16. Each case was repeated 10 times.

From the experimental result shown in Figure 7(a), we can see that the success rate of droplet shuttling decreases with the increasing number of activated electrodes without a feedback scheme. When the number of activated electrodes was 16, the success rate was only 40%. The reason for the failure is that the droplet was blocked on electrode No. 6. A larger driving time and voltage can be set to overcome this problem. However, such a configuration will not only affect the real-time performance of the DMF system but also reduce the stability of the EWOD device (the larger voltage will reduce the life of the hydrophobic layer). To solve this issue, the proposed driving and feedback scheme is integrated with the DMF system. The experimental result shows that the proposed scheme can effectively improve the success rate of droplet shuttling (i.e., the success rate can reach at least 80% with feedback). Furthermore, the proposed scheme can be applied to several DMF system droplet operations, including splitting, dispensing, and merging.

In addition, we conducted a comparison between the capacitance-based position method and the proposed scheme. Figure 7(b) shows the comparison results of the droplet motion under different control schemes. As mentioned earlier, compared with conventional capacitance-based

Figure 8: A chemical reaction controlled by the proposed system. (a) Two droplets of equal volume (D-glucose and H_2O) are observed on the EWOD chip. (b) The two droplets are driven toward the middle electrode. (c) The two droplets merge on the EWOD chip. (d) The merged large droplet is captured by the proposed system and moved to the left electrode.

sensing methods, the advantage of the machine vision-based position method is high efficiency. With an increased number of droplet movements, the detection time required by capacitance-based sensing methods is much longer than that for the machine vision-based position method. This is because the capacitance-based position method must collect the capacitance values of all electrodes every time. For EWOD chips with many electrodes, the locating time will far exceed the droplet movement time.

3.3 Droplet motion experiment: merging

Next, we used the proposed scheme to track droplets merging on the EWOD chip. Droplet merging is a commonly performed operation on EWOD chips. Merging is defined as an operation in which multiple droplets are driven to an electrode for fusion, and the merged large droplet can move successfully. This operation is widely used in chemical and biological fields. Some previous studies detected droplet merging by capacitive sensing and feedback [27,28]. However, this method is time consuming because it needs to scan every electrode.

Moreover, this method cannot identify the size of the merged droplet.

In this section, a universal chemical reaction (the droplet on the left is D-glucose , the one on the right is H_2O) is controlled and detected by the proposed scheme on the EWOD chip. The aim of this study is to observe the proposed system's performance as the droplet volume changes. As shown in Figure 8(a), two droplets of equal volume ($3\ \mu\text{L}$) are captured by the proposed system. Two droplets are driven to move toward the middle region simultaneously (as shown in Figure 8(b)). The mole values were converted to the number of molecules in $6\ \mu\text{L}$, which is the volume of the merged droplet. After the two droplets containing chemicals were merged (as shown in Figure 8(c)), the system deduced that the merged droplet volume is approximately $6.3\ \mu\text{L}$ by analysis and calculation. The experimental results show that the measured droplet volume agrees with the theoretical droplet volume.

After this experiment, we found that the driving control system applied $30\ \text{V}$ to drive the merged droplet at the beginning, but failed. According to the feedback model, the driving control system adjusted the driving parameters

Figure 9: The droplet movement performance for different liquids on the EWOD chip without feedback.

many times (i.e., the driving voltage reached 40 V) until the merged droplet moved successfully (Figure 8(d)).

Of note, droplet motion can accelerate the rate of a chemical reaction, similar to shaking a test tube to increase the chemical reaction rate. This is an advantage of the DMF system in chemical and biological fields.

3.4 Droplet status detection

In addition to droplet shuttling and merging, we also validated the proposed scheme by evaluating droplet movement effects for different liquids. All of them (i.e., DI water, PBS, and HBSS) are commonly used in chemical and biological experiments. In our experiment, different liquids were driven across a linear EWOD chip consisting of six electrodes; this was repeated 10 times for a total of 60 motions.

In general, the droplet velocity was measured for each movement. It is the ratio between the electrode length (L ; i.e., $L = 5$ mm) and the single driving time (T_d ; i.e., $V = L/T_d$) without a feedback system. However, for the proposed scheme, the image analysis system needs some time to locate the droplets. This time (T_p) is approximately 200 ms (± 50). Moreover, the driving chip (T_v) output time is approximately 20 ms. Hence, the droplet velocity was defined as $V = \frac{L \times N}{K_d \times (T_d + T_p + T_v)}$, where K_d is the number of electrode actuations and N is the number of electrodes that the droplet actually crosses in the experiment.

The droplet movement performance for different liquids on the EWOD chip without feedback is shown in Figure 9.

We know that T_d not only affects the droplet movement success rate but also determines droplet velocity. In this experiment, different liquids, DI water, PBS, and HBSS were driven across six electrodes at different velocities (i.e., different single driving times: 300, 500, 800, 1,200, 1,500, and 1,800 ms) with 10 repetitions for a total of 60 actuations. Figure 9 shows that DI water maintains a higher motion performance at high velocities (short single driving time). However, higher velocities generally result in poor droplet movement for liquids containing NaCl (PBS and HBSS). Although a longer single driving time can improve the droplet movement success rate, it may aggravate surface fouling of the hydrophobic layer [29] and reduce the real time of the system. This experiment shows that it is not appropriate to use a fixed single driving time to drive droplets. Therefore, the feedback model has good application significance for a DMF system.

The droplet movement performances for different liquids on the EWOD chip with feedback are shown in Table 3. Obviously, improvements are observed in this experiment. The number of successful movements (out of 60) increased significantly with the proposed scheme for the same droplet velocity. Particularly in complex DMF systems (i.e., multiple droplets moving simultaneously on the EWOD chip), droplet velocity should be taken into account. In addition, in this experiment, we found that a short driving time (300 ms) is favorable for liquids containing no proteins (PBS and DI water), while a long driving time (1,200 ms) is favorable for protein-rich liquids (HBSS). This observation is similar to that of the previous study [30], where a short single driving time was not enough to account for the liquid viscosity.

If the droplet is conductive and the driving voltage is DC, the actuation force in the absence of a top dielectric layer depends on the equivalent capacitance of the bottom dielectric layer [31]. On the same EWOD device, the droplet motion performance will depend on the friction force. Also, the higher friction forces is associated with high-viscosity liquids [32]. The pH of the droplet has no direct effect on the droplet movement performance.

Table 3: The performance of different liquids on the EWOD chip with feedback

Liquid type	Number of successful movements	Average velocity (mm/s)
DI water	60	10.2
PBS	60	6.9
HBSS	60	5.2

Table 4: Specific experimental parameters of the adaptive experiment

Experimental parameters	Value
Initial driving voltage	0 V
Initial single driving time	0 ms
Initial electrode	No. 5
Destination electrode	No. 8
Damaged electrode	No. 6
Electrode dimension	5 mm
Droplet radius	3.5 mm

Clearly, the experimental data generated by the proposed feedback model much better estimated the actual kinetics than those generated without feedback control. Hence, this experiment proved that the proposed driving and feedback scheme helps improve the motion performance of liquids containing NaCl by automatically optimizing the driving parameters.

3.5 Adaptive experiment

There are inevitably various failures in practical DMF applications. To demonstrate the reliability of the proposed scheme in complex DMF applications, we set up

an adaptive experiment. The specific experimental parameters are presented in Table 4. The initial driving voltage and single driving time are 0. In this experiment, we artificially burned the hydrophobic layer of electrode No. 6 using high voltage (100 V). The whole experiment is automatically controlled by the proposed system. A series of experimental images is shown in Figure 10.

After this experiment, we printed out and reviewed all the system records. First, the system calculated the droplet motion path (i.e., the shortest path method: No. 5 → 6 → 7 → 8). Next, the system activated the No. 6 electrode according to the droplet motion path. However, the droplet could not pass over the No. 6 electrode because it had been damaged (this process lasted approximately 9 s). During this process, the driving voltage and single driving time were adjusted many times (i.e., the voltage reached 40 V and the time reached 1,800 ms). In this condition, the system recalculated the droplet motion path (i.e., new path: No. 5 → 1 → 2 → 3 → 7 → 8). Finally, the droplet successfully moved to the destination electrode (No. 8). Table 5 presents the number of driving parameter modifications in this experiment. The driving time was modified 18 times. The results are consistent with our feedback model presented in Table 1. Notably, the increment of driving voltage (3 V) and time (300 ms) were set relatively low in this experiment. Such a setup is beneficial to protect the EWOD

Figure 10: A series of real-time EWOD chip images. All driving parameters are set and adjusted adaptively by the proposed system. (a) Droplet stays at No. 5 electrode. (b–e) Droplet changes motion path. (f) Droplet reaches the destination electrode.

Table 5: The number of driving parameter modifications

Driving parameters	Number of modifications
Single driving time	18
Driving voltage	10
Droplet motion path	1

chip. However, it will affect the DMF system efficiency. Specific feedback model rules can be fine-tuned for different applications (e.g., increment or driving voltage range).

Electrode damage is a kind of device defect that cannot be repaired. In this experiment, the proposed system successfully transported the droplet to the target electrode by modifying the droplet's motion path. Furthermore, the system will record the electrode number and the newest droplet motion path. The droplet will not become stuck on the damaged electrode again the next time. The experimental results revealed that the proposed mechanism has good reliability and ability to avoid interference (i.e., a damaged electrode).

The properties comparison of the proposed scheme with some previously reported control system is summarized in Table 6. The position sensing of the proposed scheme is dynamic, indicating detection, feedback, and actuation can be simultaneously realized. The driving control system has high portability and integration. Moreover, the preparation of the proposed system before detection is simple. The properties of self-adaptive of actuation parameters and recalculation of droplet motion path are also very useful for practical applications of the DMF system.

4 Conclusion

In this article, we demonstrate a driving and feedback scheme based on machine vision for a DMF system. This scheme consists of three main parts: a high-resolution camera, a computer with a graphical image analysis system, and a portable driving control system. A reference and subtracting technique with a Hough transform is used in the proposed image analysis system to locate multiple droplets on the EWOD chip. The experimental results show that the proposed system can accurately locate multiple droplets in real time. Furthermore, a feedback model is implemented in the proposed system, which is capable of detecting individual droplets merging and motion failures. It can effectively improve the

Table 6: The comparison of some previous DMF control systems and proposed scheme

System name	Sensing schemes	Position method	Motion path recalculation	Preparation before detection	Portability and integration	Reference
DropBot	Static	Electrical impedance based	No	Multiple parameters	High	Appl Phys Lett. 2013;102:193513
OpenDrop	Dynamic	Machine vision based	No	Simple	Medium	Bioengineering. 2017;4:45–61
Imaged based feedback system	Dynamic	Machine vision based	No	Medium	Low	Lab on a chip. 2017;17:3437–46
ISPSAA	Dynamic	Capacitance based	Yes	Multiple parameters	High	Micro and nano. 2020;24(8):1–9
Proposed system	Dynamic	Machine vision based	Yes	Simple	High	Our work

success rate of different droplet controls and operations. To show the adaptability of proposed scheme, we applied it to the EWOD chip with a damaged electrode without any external sensors. The proposed scheme provides a robust, high-precision, and intelligent solution for complex droplet control with performance that exceeds both manually operated and previously reported automated DMF control systems. We expect that the proposed scheme will be useful for scientists developing automated analysis platforms for a wide range of DMF system applications.

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