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A Digital Microfluidics System with Closed-Loop Feedback Droplet Sensing

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Abstract. In this paper, we present a digital microfluidics (DMF) system with closed-loop feedback droplet sensing. The system is capable of controlling the movement of droplets and detecting their positions in real time, and is compatible with different numbers of DMF electrodes. The detection of the droplet position is realized by impedance sensing. When an electrode failure occurs, the system automatically performs path planning to move the droplet successfully. Besides, we designed a voltage control unit (5V DC/AC to 80V DC/AC) to realize the voltage control for different droplets. The experimental results show that the droplet position detection time is about 2 ms, and the detection accuracy reaches 100% at 100 times. With the help of the droplet sensing system, even there`s an ineffective electrode in the origin path, the droplet was able to move to the target electrode by the replanned path. The system is expected to play an important role in many biochemical experiments due to its automation and reliability.

Keywords. Digital microfluidics (DMF); Impedance sensing; Path planning; Closed-loop feedback system.

1. Introduction

DMF systems can manipulate droplets to achieve movement, splitting and mixing, which have been used in many biochemical experiments [1-2]. These systems can be categorized into open-loop and closed-loop control systems [3-5]. In open-loop systems,

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the path of movement of the droplet, the driving voltage and the movement time are pre-setted. The open-loop system cannot detect droplet movement failure, which is essential to biochemical experiments. Therefore, there is an urgent need to incorporate a closed-loop feedback mechanism to detect and control droplets, which will improve the stability and reliability of the system.

In our past work, we used impedance sensing technique to detect the position of a droplet [6]. In this work, we propose a DMF system with closed-loop feedback droplet sensing. This system combines impedance sensing and droplet control approaches. When the droplet movement fails, the control voltage, holding time and movement path of the droplet can be changed through the feedback mechanism, which helps the droplets regain ability to move. Moreover, the time it takes to detect the position of a droplet using impedance is about 2 ms. The path planning algorithm uses the A* algorithm, which can find the optimal moving path so that the droplet can return to the pre-set path.

2. Materials and Methods

2.1. DMF Hardware System

Figure 1. DMF system and DMF chip

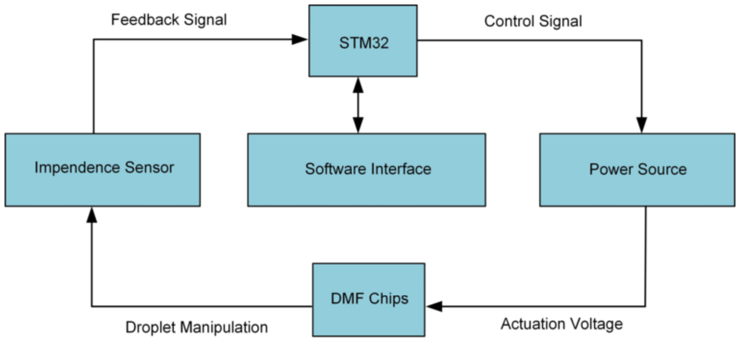

Figure 2. System block diagram

Figure 1(a) shows the hardware system (215 mm x 185 mm x 195 mm) that packages all electronic units together. The microcontroller unit (MCU) of the system is designed using STM32 from STMicroelectronics, which is used to set the power parameters and control the electrode switches. The power unit can output 5-80 V (DC or AC) and can be raised to the voltage required for the experiment. The power unit can output 5-80 V (DC or AC) and can be raised to the voltage required for the experiment. We use 35 V DC to drive deionized water (DI water). The impedance sensing unit is used to detect the droplet position with an excitation signal of 35 V, 2 kHz. The output signal is filtered and amplified by the circuitry and connected to an ADC, which is embedded in the MCU.

Figure 1(b) shows the DMF chip used in this work, which has 184 electrodes. The block diagram is shown in figure 2, where STM32 is the main controller of the system. The impedance sensing unit passes the detected signal to the STM32, and the STM32 predicts the droplet position based on the algorithm. The detection signal is transmitted to the software interface, and finally the position of the droplet is displayed on the software interface. By operating the software interface, the control commands can be sent to the STM32 through the serial port, and the STM32 processes and executes the command operations, and applies the droplet driving voltage signals to the electrodes of the DMF chip, so as to realize the motion control of the droplet.

2.2. Computer Software Control System

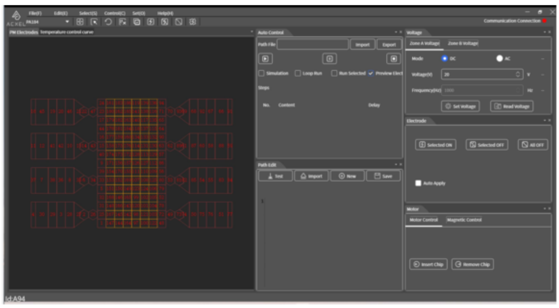

Figure 3. Software control interface

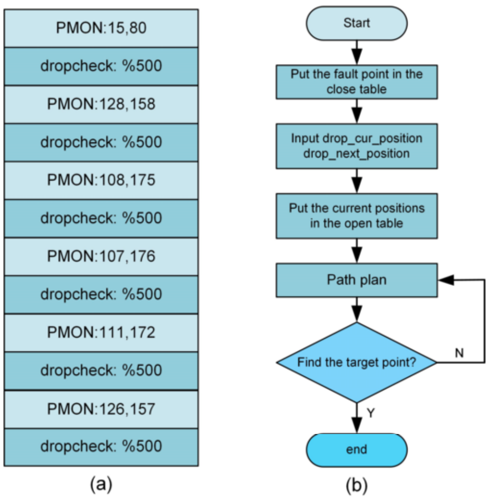

Figure 4. Path editing script and A* algorithm path planning flowchart

The software interface is shown in figure 3. With the software interface, users can send control commands to the MCU, and the MCU will execute the commands and output them to the peripheral module. The computer software control system mainly includes three control modules: power control module, electrode control module and path editing module. The power control module can realize the switching of the droplet drive signal mode. The system provides two setting modes: DC mode and AC mode. Users can select the mode as needed and raise the voltage to the specified voltage by controlling the power unit. The electrode control module allows the user to select the electrode and apply a drive voltage to that electrode to drive the droplet. Each closure icon represents an electrode on the chip. The path editing module enables the combination of electrodes to be controlled, allowing the user to edit the movement path of the droplet to accomplish different operations on the droplet. Figure 4(a) shows the script where two droplets are moved and finally merged. In the script, "PMON: 15, 80" indicates that numbers 15 and 80 are powered electrodes. "dropcheck: %500" is used to indicate that the current position of the droplet is detected and then the drive voltage of the target electrode is held for 500 ms. The hardware system transmits the droplet position information to the software interface for display so that the user can know the position status of the droplet in real time.

2.3. A algorithm*

The A* algorithm is a commonly used algorithm in graph traversal and path finding with good performance and accuracy [7-8]. The functional representation of this is as follows.

$$f(n) = g(n) + h(n) \tag{1}$$

Where f(n) represents the value of the estimation function from the starting point to the current node, g(n) represents the actual cost from the starting point to the current node, and h(n) represents the estimated cost from the current node to the end point.

The open and close tables are the two core data structures of the A* algorithm, which are used to maintain information about the nodes to be checked. During the execution of the A* algorithm, the faulty electrode is firstly added to the close table, and then the position of the current path and the next target electrode are found out. The position of the current path is firstly added to the open table, and then the node with the smallest f(n) is successively selected from the open table to be checked. If the node is the end point, the search ends; otherwise, all the neighbors of the node are added to the open table and their f(n), g(n) and h(n) values are updated. At the same time, the node is added to the closed table and its parent node information is recorded. The process is repeated until the location of the target electrode is found or the open table is empty. Figure 4(b) shows the flow of the droplet addressing algorithm based on the A* algorithm.

3. Results and Discussion

3.1. Droplet Detection

The droplet position detection technique in this work is compared with the YOLOv5 based droplet position detection image algorithm. In the experiment, we added DI water to one electrode and then used both methods to detect the droplet at the electrode. The detection performance of the two methods is shown in table 1. Detection by the impedance is faster, taking only 2 ms to complete the detection of the state of one electrode. Whereas, using the YOLOv5 based image processing algorithm takes 30 ms under GPU running state. However, both means of detection have a success rate of 100% in detecting the droplet position 100 times. Therefore, from the perspective of detection time performance, droplet detection using the impedance approach is superior to the YOLOv5-based image processing algorithm.

Table 1. Different methods for testing droplet properties (detecting one droplet)

Detection Approach	Detection time (ms)	Detection accuracy of 100 tests
impedance sensing	2	100%
image processing	30	100%

3.2. Closed-loop Feedback

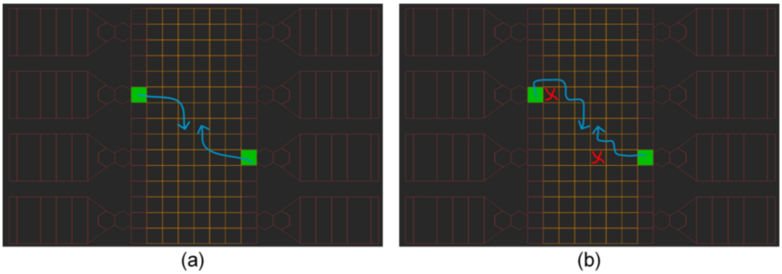

Figure 5. Droplet movement paths in different situations

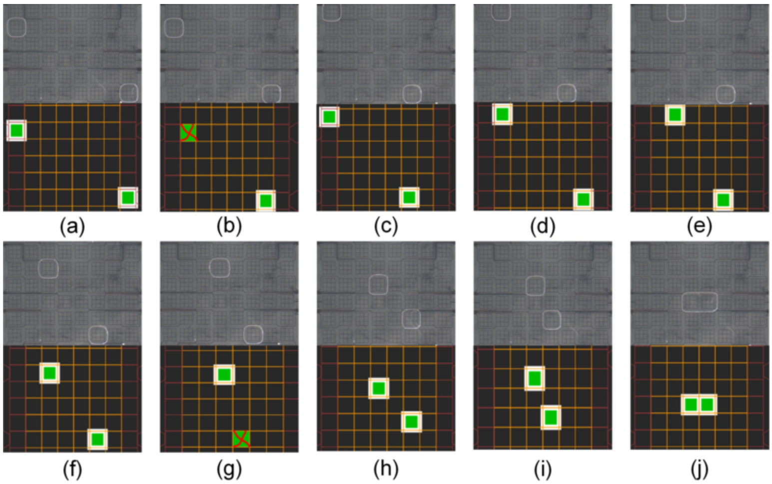

Figure 6. Real-time droplet position sensing

In the first experiment, the droplets followed a pre-set path to complete the merger. The droplet path is shown in figure 5(a). In the second experiment, the droplet merging was completed in the presence of two faulty electrodes. The droplet paths are shown in figure 5(b). Figure 6 demonstrates that the system detects the droplet position in real time. The green in the figure indicates the powered electrode, and the white indicates the droplet has been at the target electrode position. When there is an electrode failure, the droplet presence is not detected at the target electrode, as shown in figure 6(b). With the camera picture, we can find that the droplet still stays at the target electrode in the previous step. At this time, the system will recalculate the path based on the A* algorithm, so that the droplets can return to the pre-set path. From the experimental results, we can see that there is a setted ineffective electrode. The droplet path planned using the A* algorithm can avoid the faulty electrode and successfully move the droplet to the target electrode.

4. Conclusion

We propose a DMF system with closed-loop feedback droplet sensing. The system can detect the position of the droplet in real time, and when the droplet movement fails, the droplet movement path can be re-planned based on the A* algorithm, so that the droplet can regain the ability to move again. when the complexity of DMF chips increases and driving electrode are inevitable, the system helps to improve the stability and reliability of biochemical experiments.

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