A Novel Single-Fault Detection Technique of Digital Micro-Fluidic Biochip

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***Abstract*— A novel, efficient, single fault detection technique of a digital microfluidic based biochip is presented in this paper. The proposed methodology is based on parallel scanning of the microfluidic biochip by using multiple droplets. The traversal of micro-array is carried out by scanning the intermediate rows, columns and the boundaries in parallel. This technique allows us to traverse all the cells as well as all edges for detecting fault in the Digital Microfluidic Biochip (DMFB). Correctness and Dependability are the important attribute for Digital Microfluidic Biochips that are used for safety-critical applications like point-of-care health assessment, massive parallel DNA analysis, automated drug discovery, air-quality monitoring, and food-safety testing. Therefore, these devices must be tested after manufacturing and during bioassay operations. The experimental result suggests that the proposed approach is an efficient one and show significant improvement in fault detection.**

***Keywords*—Biochip, Droplet, Micro-Array, Electrode.**

I. INTRODUCTION

In recent time the microfluidic based biochips have become very popular for biochemical analysis [1]-[3]. From last few years many research works have been done on this topic. These biochips can be termed as lab-on-a-chip as it replaces highly repetitive laboratory tasks by replacing traditional bulky lab equipments with composite micro-system. It offers the advantages of design flexibility, higher sensitivity, smaller size and lower cost [4].

The microfluidic biochips are categorized based on fluid flow within it. One is traditional continuous fluid flow carried out by using micro-pumps, micro-valves and micro-channels [5]-[6]. The other one, which is an efficient approach, is to manipulate liquids as discrete droplets. The droplet based chip is referred as "Digital Microfluidic Biochip" [7]. This technique is advantageous over the continuous flow Systems [8].

We are proposing a novel and efficient technique for detecting a single fault in a Digital Biochip in this paper. The proposed technique scans the two dimensional microarray using multiple droplets in parallel to detect fault [8]. Most digital microfluidic devices consist of a two dimensional array of electrodes with one or more sources and sinks on the boundary [8].In this regular structure of biochip, the proposed technique scans the micro-array in intermediate row and column wise and in the boundary to detect the fault. In case of row wise traversal droplet goes through with the first intermediate row, starting from first column, while reaches the final column moves down one edge and back track with next row. For column wise it goes through with first intermediate column, starting from first row, while reaches last row, shift one edge right and back track with next column. In boundary the droplet start at first row, first column and moves in clock wise direction and back at the same location to complete the traversal.

The organization of the remaining paper is as follows Section 2 discuss the Preliminaries of two dimensional microarrays, their faults and graph theoretic formulation. Section 3 discusses the related prior work. Section 4 represents proposed technique. Experimental results are explained at section 5. And conclusions are drawn at section 6.

II. PRELIMINARIES

The microfluidic biochips are based on the manipulation of micro-nano liter droplets on a two dimensional electrode array using the principle of electro wetting -on-dielectric [9]. The structure of such a biochip is described below.

A. Structure of the Biochip

The basic cell of the micro-array includes a pair of electrodes that acts as two parallel plates. The bottom plate contains an array of individually controllable electrodes; the top plate is coated with a continuous ground electrode. Hydrophobic dielectric insulator is added to the plates to decrease wet ability of the surfaces and increase capacitance between a droplet and a plate. A droplet rests on a hydrophobic surface over an electrode, is sandwiched between two parallel glass plates [3], [10]. It is moved by applying a control voltage to an electrode adjacent to the droplet and, at the same time, deactivating the electrode just under the droplet. This causes the movement of the droplets towards the charged electrode. A droplet can achieve a speed of 20cm/s under a control voltage between 0 and 90V [10]. The basic cell of a digital microfluidic-based biochip is shown in Fig. 1.

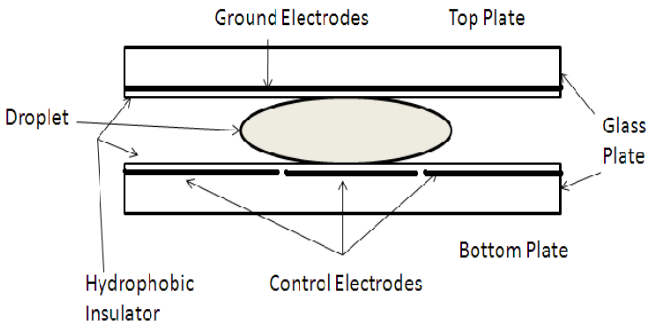

Fig. 1 Basic structure of a Digital Microfluidic Biochip

Hence a Digital Microfluidic based Biochip (DMFB) can be represented by an m×n array of individual cells. At any moment a droplet can be at any cell in the Biochip.

B. Type of Faults in a Biochip

Fault in a Digital Microfluidic Biochip can be classified as two types, Catastrophic Fault and Parametric Fault [3], [11], [12]. The Catastrophic or the hard faults which is irrecoverable, causes complete crush of the System. Most catastrophic faults result in a complete cessation of droplet transportation [11]. Thus, for the faulty system, the test stimuli droplet is stuck during its motion. While on the other hand Parametric or the soft fault does not causes system break-down but it reduces system performance immensely by decreasing motion of the droplet movement. For the fault-free system, all the test stimuli droplets can be observed to reach at the, droplet sink by the capacitive detection circuit [4].

To identify a fault, we need to pass the droplet every cell in the Biochip. That is we have to traverse the entire m×n array by moving the droplet in every possible manner. If there is any kind of fault within the chip, then the droplet will be stuck there. Otherwise it will reach the desired destination at specified time. So in order to find the fault we need to traverse the droplet from source to sink in the Biochip. Source is the point where the droplet enters into the Biochip and sink is the point where the droplet leaves the Biochip.

C. Graph Based Technique

A graph based technique can be used to detect the fault in a biochip. The structure of a digital microfluidic biochip can be represented as an m×n matrix where Cij denotes the cell at (i, j) position, and i=0 to m; j=0 to n. Where m is the number of rows and n is number of columns.

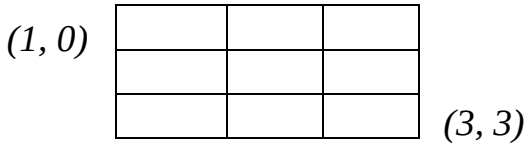

Fig.2 *4×4* microfluidic array with source (1,0) & sink (3,3)

Fig. 2 shows a 4×4 microfluidic array with source at (1, 0) and sink at the (3, 3) position. The cell (1, 0) indicates the source from where the droplet enters into the microfluidic array and starts its traversal. And the cell (3, 3) is the last cell, sink where the droplet leaves the micro array.

Now let (P_1, t_1), $(P_2, t_2)\ldots (P_k, t_k)$ are the sequence of droplet traversal from source to sink, where Pi denotes the path and ti denotes the times required for the traversal. And (Pi, ti) denote a pass. The total test time taken for traversing the entire micro array is $t_1+t_2+\ldots.t_k$. At the time of traversal if the droplet does not reach the sink even the time period is over, then it is assumed that the droplet is stuck somewhere in the micro-array, and biochip is faulty.

III. Related Prior Work

An excellent discussion of the prior work on the testing of microfluidic biochips can be found in [13]. Techniques for fault modeling and fault simulation for continuous-flow microfluidic biochips have been proposed in [14], [15].

Techniques for defect classification, test planning, and test resource optimization have recently been presented for digital biochip. Defect classification and test application procedure are described in [11]. As faults are classified as being either catastrophic or parametric, and techniques have been developed to detect these defects by electro statically controlling and tracking droplet motion path. An optimal test planning method for the detection of catastrophic faults in digital microfluidic arrays was investigated in [4], [10]. An efficient and effective integrated testing and diagnosis technique for indentifying defect in biochip has been shown in [16]. Detections of fault in micro fluidic biochips with multiple droplets in parallel are being discussed in [3], [8].

IV. Proposed Technique

In this paper we are propose a new technique for detecting a single fault within a microfluidic array. The proposed technique based on the graph based protocol. Let us suppose the m×n microfluidic biochip can be represented in terms of a graph Gm×n, where m=number of rows and n=number of columns. The droplet tries to visit as many nodes of Gm×n as possible during the first pass from source to sink. Remaining edges and nodes are traversed in pass P_2, and P_3.

For traversing the micro-array we need the droplet to enter the Biochip at the source. And after completion of the traversal the droplet leaves it through sink. In between that the droplet checks the micro-array whither there is any fault, by moving every cell and edge of the microfluidic array. Now the passes are as follows.

A. Pass One

In the first pass the droplet starts its traversal in row wise from S1 that is second row first column and moves up-to second row last column, the movement is from left to right. If it is the (m-1) th row then stop otherwise go down by one edge. Now move from right to left until the first column is reached. If it is the (m-1) th row then stop otherwise continue the above mentioned procedure to reach the sink that is (m-1) th row, first column (if number of row is even); or (m-1) th row, last column (if number of row is odd). Path of the first pass that the

droplet takes for traversing the micro array is shown in the fig. 3 by bold line. The procedure for pass one is given below.

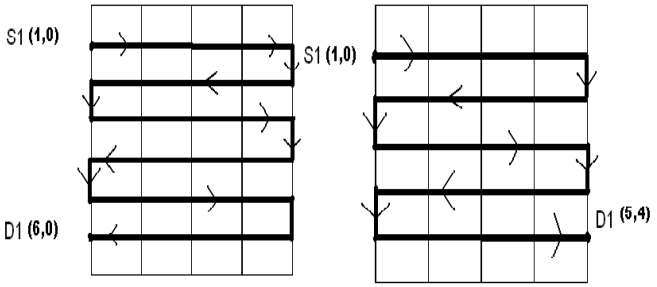

Fig. 3 Path of Pass One from Source S_1 to Sink D_1.

Procedure for Pass One

Begin

1. **While** it is possible to move further at row wise from second row first column.
   Do 2 to 5.
2. Move from left to right until the last column is reached.
3. **If** it is the (m-1) th row **then** stop.
   Else
   Go down by one edge.
4. Move from right to left until the first column is reached.
5. **If** it is the (m-1) th row **then** stop
   Else
   Go down by one edge.

End while.

End of pass one.

B. Pass Two

In the second pass droplet starts its traversal in column wise from first row second column, goes downward until reach the last row; if it is the *(n-1)* th column then stop, otherwise shift one edge right and then moves upward until reach the first row; if it is the *(n-1)* th column then stop, otherwise continue the mention procedure to reach the sink that is *(n-1)*th column, last row (if number of column is odd) or *(n-1)* th column, first row (if number of column is even). The path of the second pass that the droplet takes for traversing the micro-array is shown in the Fig. 4 by bold line. The procedure for pass two is given below.

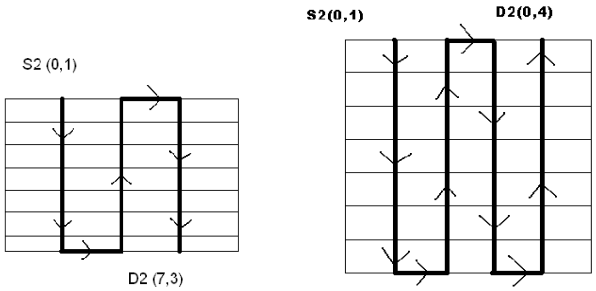

Fig.4. Path of Pass Two from Source S_2 to Sink D_2.

Procedure for Pass Two

Begin.

1. **While** it is possible to move further at column wise from first row second column.
   Do 2 to 5.
2. Go downward until the last row is reached
3. **If** it is the (n-1) th column **then** stop.
   Else
   Move one edge right
4. Go upward until the first row is reached.
5. **If** it is the (n-1) th column **then** stop.
   Else
   Move one edge right

End while.

End of pass two.

Now after the first and second passes there are still some nodes and edges left which are not traversed. And these are shown in the following figure 5.

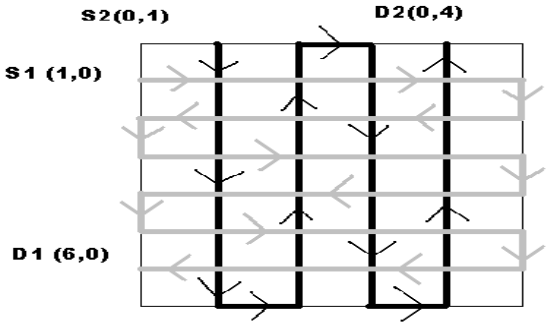

Fig. 5. After completion of Pass One and Two.

So except some boundary nodes and edges all are traversed at least once.

C. Pass Three

In the third pass the droplet starts from first row, first column and moves in the clock- wise direction along the boundary line and reaches the sink which is also first row first column. The path of the traversal is shown in the Fig. 6. The procedure for pass three is given below.

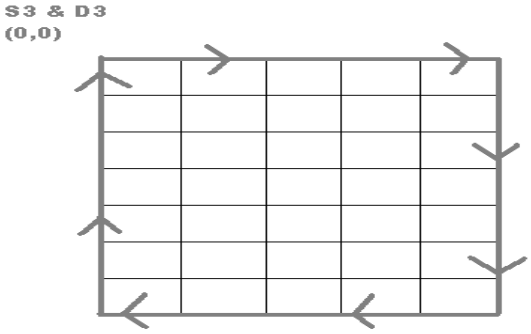

Fig.6. Path of Pass Three from Source S_3 to Sink D_3.

Procedure for Pass Three

Begin.

1. **While** it is possible to move further at boundary wise.
2. Start traversing from source, first row, first column.
3. Proceed along the boundary in clock wise direction.
4. **If** it is the sink (again first row, first column) **then** stop.

End while.

End of pass three.

Now after the completion of all three passes there are no edge and cell left which are not traversed at least once. So the traversal process is complete. If the process would carry out in sequential manner then the total time for traversal will be the sum of the times of all three passes. We are assuming that the time for a pass is equivalent to the number of edge movement in that pass. But due to parallel execution of the passes, required time for traversing of the biochip is the maximum time taken by a single pass for its completion.

V. Experimental Result

The experiment is done with large number of sample micro-arrays from 4×3 to 10×10 in Turbo C environment. Pentium III processor, 256 MB RAM and 40 GB Hard Disk are sufficient for the experiment. Following Table 1 report that the proposed technique takes lesser time compared to the Existing technique [3]. So advantage of the proposed technique is justified in all aspects over the existing one. There are six columns in the table, describing experiment serial number, size of biochip, total edges movement of the passes, maximum edges movement in a single pass, existing maximum edge movement in a single pass and percentage of improvement respectively.

Table 1. Experimental Result.

SL No	Size of Biochip	Total Edge Movement of Traversal	Maximum Edge Movement in a Pass	Existing Maximum Edge Movement	Improvement
1	4 × 3	17	10	11	9.09%
2	4 × 4	24	12	17	29.41%
3	4 × 5	31	14	24	41.67%
4	5 × 4	31	14	23	39.13%
5	5 × 5	40	16	31	48.39%
6	5 × 6	49	19	40	52.50%
7	6 × 6	60	23	50	54.00%
8	7 × 5	58	24	47	48.94%
9	7 × 6	71	29	65	55.39%
10	7 × 7	84	34	71	52.11%

VI. Conclusion

A novel, efficient single fault detection technique of a digital microfluidic based biochip has been presented. The proposed technique enables parallel testing of micro-array using multiple test droplets at the same time. Fault detection in a microfluidic biochip is an important activity because it operates in critical circumstances, as for example treating a diseased set of cells inside human body, massive parallel DNA analysis, automated drug discovery, air-quality monitoring, and food-safety testing etc. Therefore, these devices must be fault free. The experimental result indicates that the proposed method is efficient and shows significant improvement over the existing methods.

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