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Efficient Fault Detection and Diagnosis of Digital Microfluidic Biochip Using Multiple Electrodes Actuation

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***Abstract*—Nowadays, Digital Microfluidic biochip (DMFB) is a promising platform where we can concurrently execute complex bioassay operations. This automated, integrated chip is used in Many safety-critical applications like air-quality monitoring, point-of-care health assessment, automated drug discovery, parallel DNA analysis and this is possible only by deploying a robust testing mechanism. Some of the earlier reported testing and diagnosis algorithms are mostly concentrated on single fault localization or take a significant amount of time for multiple faults detection. Even in some cases, a non-faulty electrode incorrectly classified as a faulty electrode. Thus in this work, we have proposed a multiple electrodes actuation method for correct localization of the defective electrode(s) within very less time. Moreover, when some other bioassay operations are running in a biochip then also our proposed method can diagnose the faults of the biochip.**

***Index Terms*—Biochip, electrowetting, Peripheral test, RPT, MEAT, CPT, fault model, test time**

I. Introduction

Over the last past decade, composite microsystems incorporates the microelectromechanical (MEMS) and microelectrofluidic systems (MEFS) as the next generation of system-on-chip designs [1]. These new kind of integrated automated systems replace the traditional cumbersome laboratory equipment with miniatured devices which offer higher sensitivity and fast turn around time for analysis. It has less likelihood of human error and cost-effective due to the small sample and reagent volumes. Microfluidic biochips categorize as *Continuous Flow Biochips* [2] and *Digital Microfluidic Biochips* [3]. Continuous Flow Biochip uses a large number of microvalves and micropumps are used to control different fluidic operations. Digital microfluidic biochip overcomes this situation and enables us to control discrete nano-litre (μl) droplets precisely. The droplets are the biological samples that move around the patterned array of individually controlled electrodes by the process of electrowetting actuation.

The system complexity and the integration complexity rapidly increased due to the massive parallelism of bioassay operations running concurrently on the biochip. Thus, the yield rate tends to decrease due to the increase in chip density. Hence, device manufacturers are searching for inexpensive processes and materials which can optimize the cost of manufacturing disposable device. So, for the competitive global market of disposable biochips, a very cost-effective test plan is needed to test the health of the chip for further operations. In the past few years, biochip testing got much attention to ensure the dependability of the biochip. In a broader sense, two types of testing are there, one is structural testing [4] and another is functional testing [5]. In this work, we mainly focus on the structural testing of the biochip and the following are contributions of our work.

1) Proposed testing and diagnosis scheme senses the faulty position effectively within very less time.
2) In this scheme testing and diagnosis is used in an interleaved fashion to identify the multiple numbers of faults.
3) This method is used for online testing as well as offline testing.

The sequel of the paper is as follows. Section II presents the motivation of the proposed work. Section III describes the fault model and problem definition. In section IV, we discuss the working principle of the proposed method. Section V presents the simulation results and the comparison with other methods. Finally, Section VI concludes the work.

II. Motivation

Here we highlight some of the problems which are not solved by many popular testing and diagnosis algorithms. These problems are as follows.

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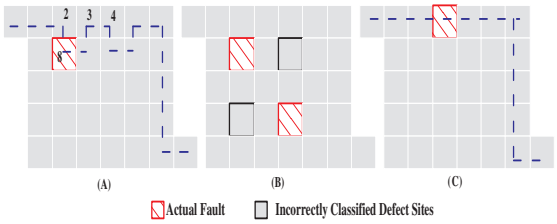

Fig. 1. (A) Unidentified faulty electrode using Interleaved Zig-zag Algorithm (B) Classified non-faulty site as a faulty site using PSL (C) Fault in the peripheral

1) **Inappropriate Routing path design:** One or more droplets are routed from a specified source to destination by following a predefined test path to detect the faults of an electrode. After a specific time slot if the droplet(s) fails to reach the sink, then we conclude that the routing path is the faulty path. In Fig. 1(A) we are following *Interleaved Zig-zag Algorithm* [4]. The electrode open fault in the 8^{th} electrode remains undetected due to improper routing path design. A similar situation also arises in the other algorithms as in [4].
2) **Incorrectly classified faulty site:** One of the most vital drawbacks of the parallel scan like (PSL) test [6] is to incorrectly specify a non-faulty electrode as a faulty electrode as shown in Fig. 1(B).
3) **Faulty Peripheral:** If any faulty cell exists in the peripheral (shown in Fig. 1(C)) then the chip can not be tested using the methods discussed in [4], [6], [7]. But our test and diagnosis methodology capable of identifying any fault location even if it exists in the peripheral.
4) **Testing & Diagnosis time:** Here tests and diagnose are used in an interleaved manner. So, any faulty cell identified in the diagnosis phase can be bypassed from testing in the next phase. Hence, the test time reduces dramatically compared to [6], [7]. Our method also has a great impact on the diagnosis time.

Here, we propose a methodology named MULTIPLE ELECTRODES ACTUATION TEST (MEAT) to overcome all of the above discussed drawbacks and to identify multiple faults. Using our model we can check the correctness of the biochip and also being able to locate the faulty cell(s).

III. FAULT MODEL AND PROBLEM DEFINITION

DMFBs have some unique failures like any other microelectronic devices. Hence, different fault models are suggested to identify those faults with a layer of abstraction. There are two types of structural faults. These are *electrode open faults* [3] and *electrode short faults* [8]. The first kind of fault occurs due to a lack of connection between the voltage source and the electrode. The second type of fault occurs when a droplet gets stuck between two adjacent electrodes. Here, we suggest a test method based on the total number of droplets detected at the destination. Instead of using a single capacitive sensing circuit, here, we use two capacitive sensing circuits. The first one is attached to the destination and the second one is attached to the source. Each droplet has a unique detection time at the destination and the output of the first capacitive sensing circuit helps us to know whether this droplet is detected or not. If you find that some of the droplets are missing in the destination, then the biochip is a faulty chip. Then we use the second capacitive sensing circuit to diagnose the fault location. Thus, we propose an algorithm named *Multiple Electrodes Actuation Test (MEAT)* (as shown in Algorithm 1) which can identify the multiple faults within a very small amount of time. Now, formally the problem can be stated as follows.

Given: Any rectangular biochip of size $M \times N$.

Objective: To detect and determine the exact locations of f number of faults present on this biochip.

IV. PROPOSED METHOD

In this work, we are using two capacitive sensing circuits, the first one is used at the source and the second one is used at the sink. From the starting point to the destination the movements of the test droplets are described by a set of the alphabets $\{d, r\}$. Here d, r denote the movement of the droplet to the down and right respectively from a specific position.

Our proposed method comprises of four individual steps. The first step is the *peripheral test* that checks the correctness of the boundary cells. If we find any fault at the peripheral then we will use the *MEAT* step to find the faulty cell x and will add it to the faulty list F. We bypass the cells in F in the next step known as *Row-wise Path Test (RPT)*. In this step, we will find out the fault of the non-peripheral cells. If any fault is identified then the $MEAT$ step is applied to know the fault location. Now, if the fault type is *electrode short fault* and orthogonal to the droplet movement then the fault is not identified in the *RPT* step. Hence, the last step *Column-wise Path Test (CPT)* is used to ensure that the biochip is fault-free. So, if any fault is identified in the last step, it means that the type of fault is *electrode short fault*. The following are the basic steps of this algorithm:

1) **Peripheral Test:** Boundary cells are known as peripheral cells. Two different test droplets are used to visit all the peripheral cells. The first one visits all of the top and right side cells and the next one traverses all of the remaining peripheral cells of the biochip. If any droplet fails to reach the destination within a specific time unit, it means that the *peripheral test* failed. Thus we have to identify the error that exists in the peripheral cells. Hence, instead of doing the *Row-wise Path Test (RPT)*, we use the *Multiple Electrodes Actuation Test (MEAT)* step to identify the faulty cell x and will add it to the fault list F.
2) **Row-wise Path Test (RPT)**: This step is requires to know which particular cell in the row-wise direction is faulty. Multiple droplets traverse in row-wise fashion through $DMFB$. For the first iteration, droplets traverse row wise through *DMFB*. Then in the next iteration, droplets move through even-numbered rows only. For any $M \times N$ biochip the default droplet movement can be described as $rd^{i-1}r^{N-1}d^{M-i}r$, where $1 < i < M$.

Here the trajectory path is denoted by i and it is counted from the top. Consider the biochip of size 5×10. For $i = 2$ the string value is $rd^{2-1}r^{10-1}d^{5-2}r = rdr^9d^3r$ shown in Fig. 2. If the previous step fails, then we have to bypass those faulty cells to this step. If any droplet fails to reach the destination within a specific time unit, it means that the fault(s) exist(s) in this path. Now we have to identify the exact location of the faulty electrode using *MEAT* step.

3) **Multiple Electrodes Actuation Test (MEAT)**: This step is independent of any other step and it is applicable when any droplet gets stuck anywhere in the biochip. In this step, more than one electrodes are actuated at the same time with a sufficient gap between two consecutive actuated electrodes to prevent unwanted droplet operations like splitting and merging. If any droplet gets stuck in the path P then $MEAT$ is used to know the fault location. For each electrode E_i we assign a sequence number S_i where $1 \leq i \leq (length\, of\, path\, P)$. For any two consecutive sequence $\{S_i, S_j\}$, $|S_i - S_j| = 1$. We diagnose only the unvisited electrodes in the path P to know the exact faulty location. Here, we only consider the electrode open fault. So, if the fault exists in E_i, it means the droplet is stuck at E_{i-1} in the path P. If the droplet is stuck at E_{i-1} , then it moves in the backward direction using the same path P. If the droplet stucks at E_i then the 1^{st} clock cycle E_{i-1} actuates. After that in the 2^{nd} clock cycle, E_{i-2} actuates and so on. If the droplet is detected at the source then the fault location is identified, else this step is repeated for the next probable fault position at E_{i+1}. In this scheme, we can test more than one faulty position if certain conditions are met. The conditions are as follows.
   a) We can generate the actuation sequence for the electrode E_i if the testing of all electrodes upto E_{i-1} has been finished.
   b) When we reach the 3^{rd} clock-cycle of any actuation sequence for probable faulty electrode, then we can start the sequence for the next probable faulty position.
4) **Column-wise Path Test (CPT):** This additional step is required to assure that the biochip is fault free. Like the RPT step, this step is repeated twice. In the first step, droplets are positioned in the even-numbered columns and traversed column-wise manner. Similarly, in the next step, the droplets are placed in the odd-numbered columns. The trajectory path of the droplet is described by the string $r^{N-i+1}d^{M-1}r^i$, where $1 < i < N$. Here the trajectory path is denoted by i and it is counted from the right. Any fault found in a path is identified as electrode short fault. Hence we have to use the modified $MEAT$ step to know the position of the faulty cell which is not discussed in this literature. An illustrative example presents the multiple electrodes actuation step.

Example 1: Consider the biochip of size 5×11 shown in Fig. 2 where a droplet is stuck at electrode number 4 due to an *open fault* at electrode number 5. Assume that peripheral test ran successfully. Next, we apply RPT, but if the test droplet gets stuck at anywhere in *row 2* (as shown in Fig. 2), we need to identify the stucked location. Hence, we have to apply *MEAT* to know the faulty location. The entire actuation steps with the clock cycle (s) are shown in Table I. If peripheral test executes successfully then any of the electrodes between 3 to 10 (as shown in Fig. 2) may be identified as a faulty electrode. So, the droplet might have stuck at any position between electrodes 2 to 9. Thus, at the first clock cycle, we actuate the first electrode. If the droplet stucks at 2 then it automatically moves to the first electrode and will be detected by the sensing circuit attached with the source. As the sensing circuit does not detect anything, we can conclude that electrode number 3 is not faulty and the fault may exist in any position between 4 to 10. Now, start testing electrode 4 and see Table I. As the sensing circuit does not detect anything at the third clock cycle, we can conclude that electrode number 4 is not faulty and the fault may exist in any position between 5 to 10. At the sixth clock cycle we actuate electrode 1 and 4 at the same time. This is possible because we already reach the 3^{rd} clock cycle for the next probable faulty position which is electrode 5. As the test droplet is detected at the source, so we can conclude that electrode 5 is defective. In this way, we can repeat the *MEAT* to identify the fault in other electrodes.

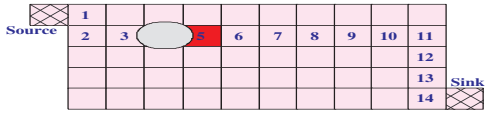

Fig. 2. Droplet stucked at Electrode 9

TABLE I
DETECTION OF THE STUCKED DROPLET OF 5×11 BIOCHIP

Clock Cycle	Actuated electrode Sequence number	Status of Droplet detection at source	Conclusion
1	1	No	Electrode 3 Non-Faulty
2	2	No	Inconclusive
3	1	No	Electrode 4 Non-Faulty
4	3	No	Inconclusive
5	2	No	Inconclusive
6	1, 4	No	Electrode 5 Non-Faulty

We show that for any $M \times N$ biochip the total testing time in off-line mode is $(T) = 4M + 4N - 11$. It means that up to CPT step we need this amount of time. For online testing, the total testing time varies due to the waiting time for the "obstacle" [3]. Thus the incurred test time for on-line testing is equal to the summation of actual time (T) and the total waiting time. $MEAT$ is also applicable for multiple fault diagnosis. If the average number of steps for a single fault is n then the whole diagnosis time to detect K number of defectss is $DT = Kn + B_p - 1$. Here, B_p denotes the total number of cells during the bypass of all the identified faults in the same path.

Algorithm 1: Algorithm MEAT

```
Input : M × NBiochip
Output: Faulty Set F
if Peripheral Test fails then
    do MEAT to identify the faulty cell and add to faulty list F
else
    foreach Unvisited Row-wise path p do
        Do Row-wise path Test bypassing F
        if p fails the Row-wise Test then
            do MEAT to identify the faulty cell c add to the faulty list F
        end
    end
    foreach Unvisited Column-wise path p do
        Do Column-wise Path Test bypassing F
        if p fails the Column-wise Path Test then
            Then p contains electrode short fault
            Do Modified_MEAT to identify the faulty cell c add to the faulty list F
        end
    end
end
```

TABLE II
COMPARISON OF TEST AND DIAGNOSIS TIME BETWEEN MEAT AND ALGORITHM [3], [9]

M× N	TT (OF)			TT (SF)	DT		%Imp
	[9]	[3]	MEAT	MEAT	[3]	MEAT	DT
4×5	20	16	16	25	1.38	0.31	77.54
5×6	26	21	21	33	1.88	0.44	76.6
6×7	32	26	26	41	2.5	0.56	77.6
7×8	38	31	31	49	3	0.69	77
8×9	44	36	36	57	3.5	0.81	76.86
10×10	53	45	45	69	4.44	0.94	78.83

V. Simulation Result

In this section we have compared our method with the algorithms presented in [4], [6], [7], [9]. We made comparisons based on two parameters. These are Test Time (TT) and Diagnosis Time (DT). Table II presents all the comparison between the test time of MEAT and the methods presented in [3], [9]. In Table II we have shown the electrode open fault ($TT(OF)$) as well as the electrode short fault ($TT(SF)$) of $MEAT$. The diagnosis time (DT) in CPU time and the average improvement of the diagnosis time in percentage ($\%Imp$) with the diagnosis time of [3].

In Table II the comparison between $MEAT$ and the algorithms [9] has been shown. Here we can see that $MEAT$ has reduced the average test time by 17.84%. By using a *50 V* actuation voltage and switching frequency of *16 Hz* [10], we can transport a droplet to the next cell within *62.5 ms* which is equal to the time slot length. In average $MEAT$ takes 0.62 sec to diagnose a single fault. Though the algorithm presented in [3] and $MEAT$ takes equal amount of time but the diagnosis time is much better than earlier. Table II shows that $MEAT$ achieves the average reduction of diagnosis time by 77.4% , compared to the algorithms reported in [3]. Table II shows that our proposed method is much better than the methods presented in [9] and [3]. Figure 3 shows the comparison between the incurred test time of *MEAT* and other algorithms. Fig. 4 shows that the diagnosis time of $MEAT$ is much better than the method based on the *Euler path*.

VI. Conclusion

In this work, we propose a heuristic algorithm to minimize the test time of regular shaped $DMFBs$. Our proposed algorithm *MEAT* can test and diagnose the biochip even when the fault exists in the peripheral. This algorithm can also precisely locate the faults within very less time. Here we use testing and diagnosis steps interchangeably that reduce the incurred testing and diagnosis cost. Moreover, we use multiple droplets for testing, which gives a better result compared to the existing algorithms.

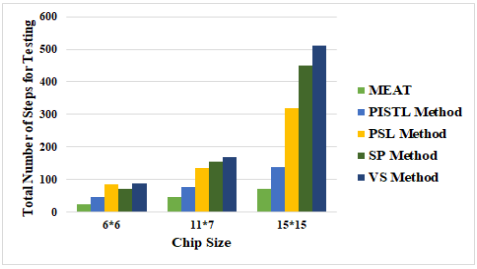

Fig. 3. Comparison of the test time among the proposed method MEAT, Pipelined Scan-Like Test (PISTL) [7], Parallel Scan Method (PSL) [6], Scan Path-based Method (SP) [6] and Vertical Strip Method (VS) [4]

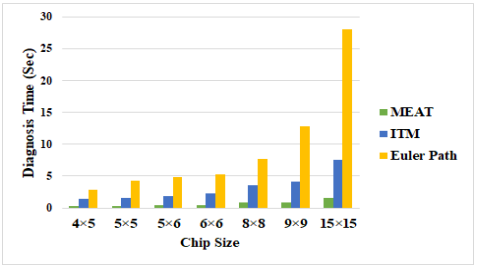

Fig. 4. MEAT is compared with ITM [3] and Euler path based algorithm [8]

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