Journal of Electronic Testing (2023) 39:89–102
https://doi.org/10.1007/s10836-023-06048-9

Fault Detection and Diagnosis of DMFB Using Concurrent Electrodes Actuation

Sourav Ghosh[1] · **Surajit Kumar Roy**[2] · **Chandan Giri**[2]

Received: 15 October 2022 / Accepted: 31 January 2023 / Published online: 27 February 2023

Abstract
Digital Microfluidic Biochip (DMFB) is a heartening replacement to the conventional approach of biochemical laboratory tests. Air quality monitoring, point-of-care health monitoring, automated drug design, and parallel DNA analysis are just a few of the uses for these integrated devices. These applications prioritize the necessity of a cost-effective testing process to ensure the correct functionality of the biochip. Many of the testing mechanisms reported in the various literature concentrated on single fault identification or took a considerable amount of time to detect more than one fault. Thus a cost-effective testing and diagnosis method is required to minimize the incurred testing and diagnosis time. Hence, in this literature, we propose a method with the flexibility to simultaneously actuate more than one electrode. This method also facilitates chip testing offline as well as in online mode.

Keywords Peripheral test · RPT · MEAT · MMEAT · CPT

1 Introduction

Over the last decade, integrated circuit testing research has expanded beyond digital evaluations to cover analog and mixed-signal devices. As the next generation of system-on-chip architectures, these composite microsystems include microelectromechanical systems (MEMS) and microelectrofluidic systems (MEFS) [27]. Such automated sensing devices replace the traditional cumbersome laboratory equipment with a miniature integrated device. It can offer higher sensitivity and a fast turnaround time for analysis. Moreover, these devices can operate without human intervention, so there is less likelihood of human error and are cost-effective due to the small sample and reagent volumes. Microfluidic biochips can be categorized as follows,

- *Continuous Flow Biochips:* The Continuous Flow Biochips [25] are made up of a micro-capillary channel that is permanently etched and through which a continuous flow of fluid travels. External pressure sources, such as mechanical micropumps, or electrokinetic mechanisms, such as electro-osmosis, carry out various fluidic actions. Many integrated micro-pumps and micro-valves manage the many fluidic parameters, making them hard to control.
- *Digital Microfluidic Biochips:* In the recent advancement of biochip makes possible to use of discrete nano-liter (μl) droplets rather a continuous flow of fluid. These discrete droplets can be controlled precisely to perform different fluidic operations. It consists of a patterned array of individually controllable electrodes on which the biological samples are moved. Due to their two-dimensional scalable architecture, these new biochips allow additional flexibility and can dynamically remap [15] any fluidic operation from one location to another.

Recent technological advancements of DMFBs incorporate different types of sensors to analyze different types of

Responsible editor: K. Chakrabarty

Surajit Kumar Roy and Chandan Giri both contributed equally to this work.

✉ Sourav Ghosh
sourav.of.25@gmail.com

Surajit Kumar Roy
suraroy@gmail.com

Chandan Giri
chandangiri@gmail.com

[1] Computer Science & Engineering, Institute of Engineering & Management, Kolkata, India

[2] Department of Information Technology, Indian Institute of Engineering Science and Technology, Shibpur, India

activities. For example, integrated waveguides [8], capacitive sensors [3], or CCD cameras [16] are used to monitor bioassay operations. We allowed more processes to run concurrently to improve the overall system throughput, which increased the system and integration complexity. Thus it increases the chip density and, at the same time, decreases the yield rate. Hence, to lower the manufacturing cost of disposable devices, the device manufacturer continuously searches for inexpensive processes and materials. However, the current generation of DMFB technology has a number of flaws, including variable droplet size and insufficient integrated sensors for real-time droplet identification. Micro-electrodedot-array (MEDA) design has recently been presented in [30] as a solution to these restrictions. The use of oscillation-based testing methods as an off-line error detection tool for MEDA-based DMFBs has been suggested in [17]. Despite these improvements, cross contamination remains a key drawback of today's DMB platforms. Acoustofluidics, a contactless liquid-handling biochip technology, has been presented in [31] as a means of overcoming this restriction.

Biochips are employed in various safety-sensitive applications, such as health evaluation and infectious disease screening, where reliability is vital. Furthermore, when the biochip is deployed for pharmacological procedures such as drug design and discovery, the process necessitates a high level of precision. Some of the faults are caused by an unpleasant and hostile operating environment in the biochip. Biological samples (e.g., proteins) residue may contaminate other particles during field operations, resulting in improper sample processing. Due to the competitive global market for disposable biochips, a cost-effective test plan is necessary to ensure the chip's condition for future operations. Biochip testing has received much interest in recent years as a way to assure the biochip's durability. Biochip testing can be classified into the following categories in a general sense:

- *Structural Testing:* Structural testing [13] aims to know any electrode's physical defects. Due to the physical defects, a droplet may get stuck in the biochip. This literature mainly focuses on structural testing to identify the two types of faults: *electrode open fault* and *electrodes short fault*.
- *Functional Testing:* Functional testing [12] is an extension of structural testing. More than one electrode can be grouped in the biochip to form a functional unit like a mixing unit or a splitting unit. However, due to fault in any electrode, anybody might get a wrong result. For example, in the splitting operation, the same actuation voltage needs to apply two adjacent electrodes of the droplet. Fault in any of the adjacent electrodes may produce non-uniform-sized droplets.

A unified test methodology that uses a droplet to test a biochip is discussed in [22]. A new test path optimization method based on priority strategy and genetic algorithm is proposed in [7]. In [2], an Integer Linear Programming (ILP) model subject to various physical limitations is provided. The methods suggested in [2] are applicable to any arbitrary layouts. Here, the proposed method mapped the problem as *min-max K-Chinese Postman problem*, which is *NP-hard*, when there are two or more test droplets. A serial structure for online testing of digital microfluidic biochips is proposed in [11]. An ant colony-based testing path optimization algorithm for online testing is proposed in [28]. The test planning method presented in [20] is based on the Hamilton cycle problem. However, it takes a long time because it is NP-Hard. As a result, a computationally intensive heuristic strategy based on the Monte Carlo simulation is suggested in [23]. This approach lacks adaptive testing, in which the test application must change in response to fault detection. This test plan is also unsuitable because the fault diagnosis technique targets a specific biochip with fixed array size. As a result, a different graph-based solution based on the Euler path [21] is suggested. This method efficiently locates the electrodes' short fault. However, the suggested method requires a lengthy test application time to traverse an entire biochip using a single droplet. Regardless of the size of the microfluidic array, this method uses one droplet to traverse the entire array. Defect-free cells are tested for fault diagnosis in the Euler path. As a result, finding an electrode open defect takes a long time. The cost-effective multiple droplets approach provided in [1, 4, 9] can shorten the duration of the test. The multiple test plan suggested in [4] only functioned in offline mode and could not find the exact position of the defective electrode (s). An alternative multiple test approach described in [26] cannot identify the issue when the multiple faults are present in multiple rows and columns. We have highlighted the advantages and disadvantages of other methods in Table 1. For MEDA biochips, effective built-in self-test (BIST) design presented in [10]. Another fault recovery for MEDA biochips using an IJTAG Network has been presented in [29]. The followings are the contributions in this work.

- Using this algorithm we can identify the type of faults and also can locate the fault position(s) within very little time.
- Within very less time we can diagnose more than one fault.
- Electrodes short fault identification is a very challenging and time consuming task. Here we are mainly focusing on fault identification of electrodes short fault and our proposed algorithm also can take very less amount of time.
- In this scheme, we are using testing and diagnosis in an interleaved fashion which causes the reduction of the overall testing and diagnosis time.
- The proposed approaches are used for online testing as well as offline testing.

Table 1 Other Testing and Diagnosis Methods with Pros and Cons

Method name	Testing	Diagnosis	Comments
Method based on ILP	yes	no	only suitable for moderate chip size
Method based on Hamiltonian Path [20]	yes	no	it is an NP-Hard problem and it can detect only electrode open fault
Method based on Euler Path [21]	yes	yes	huge testing and diagnosis time
Method based on Parallel Scan Like Test [26]	yes	yes	is not suitable for multiple faults testing and diagnosis

The following is the paper's conclusion. The suggested work's motivation is presented in Section 3. The fault model and problem definition are described in Section 4. The proposed method's working principle is discussed in section 5. The simulation results and comparisons with other approaches are shown in Section 6. Finally, Section 7 brings the process to a conclusion.

2 Overview of Digital Microfluidic Biochips

In a DMFB, the droplet is manipulated using the phenomena of electrowetting actuation [14]. Interfacial tension is established in electrowetting actuation by introducing an electric field between the conductive fluid and a solid electrode. A primary cell of DMFB consists of two parallel glass plates with a filler medium of silicon oil sandwiched between the plates. Highly polarizable and conductive droplet sandwiched between the plates, and it is moving through this filler medium. The bottom plate of DMFBs is a patterned array of individually controllable electrodes, whereas the top plate is the continuous ground electrode shown in Fig. 1. Here droplet volume is slightly higher than the pitch of the electrode to maintain the sufficient overlapping between the droplet and the neighboring electrodes. In Fig. 1 the current position of the droplet is electrode 3. Hence, to move the droplet to its adjacent electrode, a time-varying voltage is applied to the adjacent electrode. At the same time, instance electrode 3 is deactivated, which creates a surface energy gradient that forces the droplet to move onto the charged electrode. The existence of the droplet at the sink or source is detected using a capacitive sensing circuit, as shown in Fig. 2. The droplet is dispensed from a reservoir, and then it is routed, split, merged, and mixed based on electrowetting actuation [14].

3 Motivation

Some well-known testing and diagnosis algorithms facing some technical challenges, which are emphasized in this section as follows,

- **Inappropriate routing path design:** To identify the faulty location, we have to route one or more test droplets using a predetermined routing path from one specified source to the destination. If the test droplet is identified at a specific time interval, we can conclude that the routing path is error-free. It can be shown that this criterion is not enough for biochip testing. In Fig. 3a, we have used *Interleaved Zig-zag Algorithm* [13] to illustrate this overwhelming situation. In this figure, we are transporting a test droplet through a predetermined routed path which is shown in we have used *Interleaved Zig-zag Algorithm* [13] to the dotted line for expressing the actual routing path. Here we have assumed that an *electrode open fault* exists in the 8^{th} electrode. Now, the 3^{rd} electrode actuates, which forces the stucked droplet at electrode 2 to its actual path. Hence the fault remains undetected, and this prob-

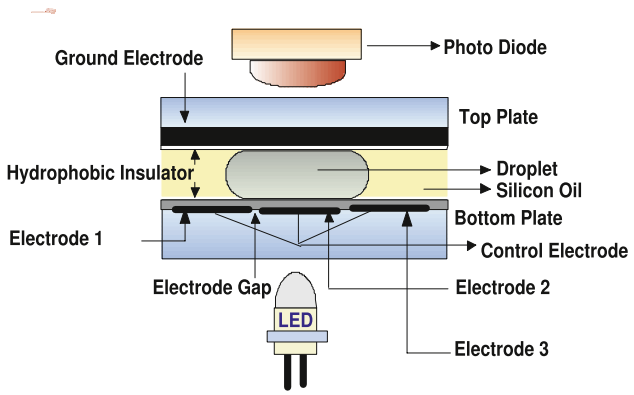

Fig. 1 Schematic diagram of DMFB (Fig. 1 [5])

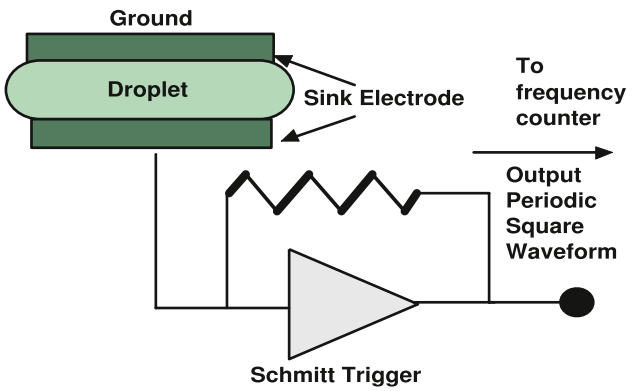

Fig. 2 Schematic diagram of Capacitive-sensing circuit (Fig. 2 [5])

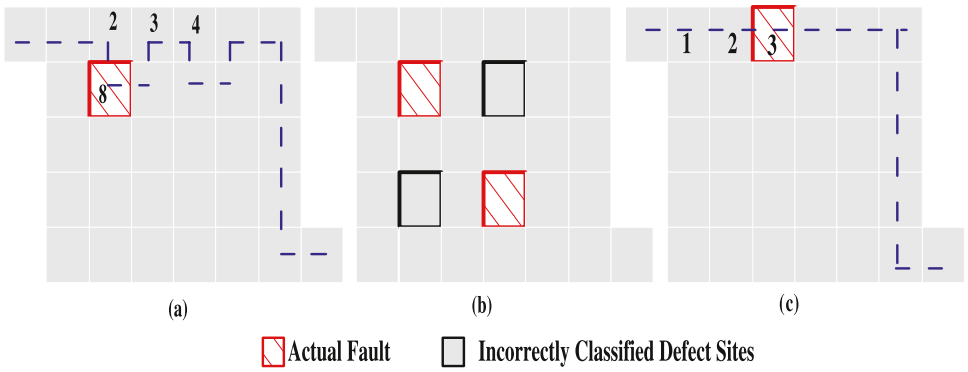

Fig. 3 **a** Unidentified faulty electrode using Interleaved Zig-zag Algorithm, **b** Classified non-faulty site as a faulty site using PSL, **c** Fault in the peripheral (Fig. 2 [6])

lem occurs due to inappropriate Routing path design. All the algorithms discussed in [13] suffered from this error.

- **Incorrectly classified faulty site:** This problem occurs more explicitly when the faulty position is diagnosed using the parallel scan-like test [26]. If more than one row or column intersects, we will get multiple intersection points that cause us to detect a non-faulty site as a faulty site which is shown in Fig. 3b.
- **Faulty boundary cell:** Many popular algorithms use the boundary cells to route the test droplet. However, none of these algorithms discussed the situation when the fault exists in the boundary cell. In the case of many popular algorithms [9, 13, 26] the rest of the steps depend on this step. So, any fault in the boundary cell fails the execution of these algorithms. In Fig. 3c, we have shown that using *Parallel Scan Like Test*, a test droplet never rich to the sink due to the presence of a fault in electrode 3. The other popular algorithms presented in [9, 13] also suffer from this issue. So, in this literature, we have addressed a solution to overcome this issue. Though, we fail to provide any solution in case of *electrodes short fault* in the boundary cells.
- **Testing & Diagnosis time:** Reduction of overall testing and diagnosis time is the prime objective of any testing and diagnosis algorithm. In our proposed methodology, we can use the testing and diagnosis step interleaved manner. So, any cell identified as faulty can be ignored in the following testing step, which causes the reduction of overall testing time compared to other algorithms in [9, 26]. Due to multiple electrodes, we can also reduce the overall diagnosis time.

To overcome all of the foregoing issues, we offer a methodology named Multiple Electrodes Actuation Method (MEAM). Using our model, we can check the correctness of the biochip and also be able to locate the faulty cell(s).

4 Fault Model and Problem Definition

DMFBs are likely to fail like any other microelectronic circuit, which drifts its operation from the specified behavior. Hence a layer of abstraction is used to identify the cause behind this failure. Using this fault model, we try to identify the physical defects in any electrical or fluidic domain. The type of faults is broadly classified into two types: catastrophic and parametric [19] faults. The catastrophic fault is a soft type fault that causes the complete breakdown of the system. However, the parametric fault occurs due to the deviation of the geometric parameter. This type of fault is hard to detect and reduces the system's performance adequately. However, the catastrophic faults may halt the droplet transportation completely. In Table 2, we discuss some of the common errors which are familiar to DMFB. This literature mainly concentrates on detecting two types of faults, electrode open faults and electrodes short fault [1, 18, 24]. The most common type of fault is an electrode open fault, which is quite easy to spot. It happens when the electrode and the

Table 2 Some common failures in the DMFBs

Source of failure	Defect	Fault Model	Observable Error
Excessive voltage applied to the electrode	Dielectric breakdown	Short between the electrode and the droplet	Prevents droplet transportation
	Short between adjacent electrodes	Electrode short	Droplet get stucks between sorted electrodes
Error in fabrication	Open connection between control source and control wire	Electrode open	Droplet get stucks due to non-activation of the electrode
Particle contamination	Fluidic high impedance between plates	Fluidic open	A droplet cannot move across the obstacle

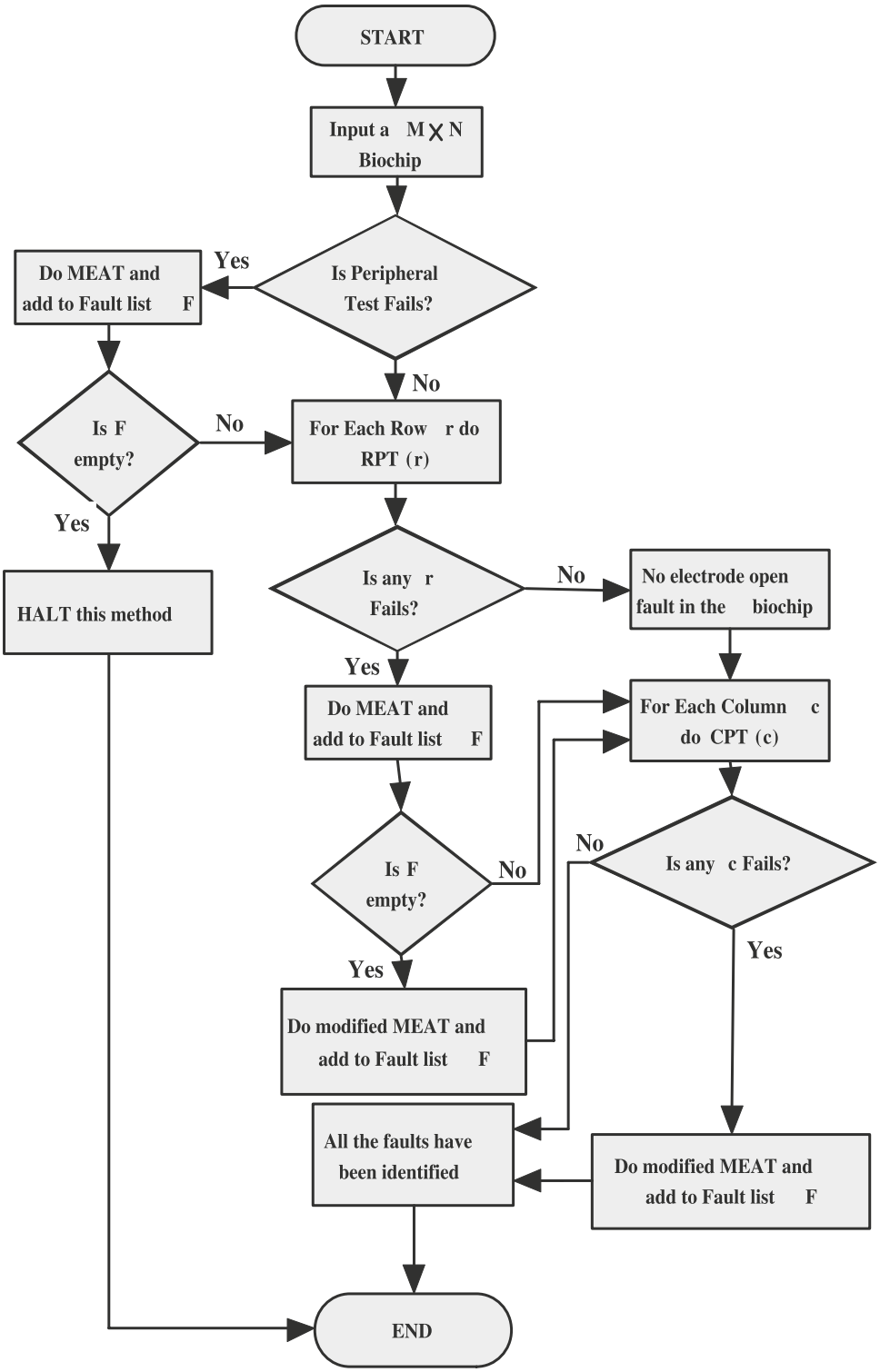

Fig. 4 Flowchart of Multiple Electrodes Actuation Method

voltage source become separated. Whereas electrodes short fault occurs when a droplet is permanently stuck between two adjacent electrodes. Our objective is to route multiple test droplets via different routes based; on the outcome; we can detect the position of the faulty electrode(s). Thus, we bring forward a *Multiple Electrodes Actuation Method (MEAM)* by which we can identify the multiple numbers of faults within a very less time. The flowchart of *MEAM* is shown in Fig. 4. Our problem is composed as follows:

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

Output: A set of faulty set F.

Objectives:

- We can test and diagnosis all the faulty electrodes.
- It must satisfy all the fluidic constraints.
- Overall testing time can be minimized.

5 Proposed Method

Here we use two capacitive sensing circuits. The first sensing circuit is connected with the source, and it's used for diagnosis purposes. The second one is connected with the sink. Any droplet movement is described by a set of alphabets which is d,r to denote the movement of a droplet to the *down* and *right* from the current position. There is total of five steps in the *MEAM* method. Out of all those steps only three are mandatory: *peripheral test (PT)*, *Row-wise Path Test (RPT)* and *Column-wise Path Test (CPT)*.

The first step is the *PT* and also the core of other subsequent steps. The primary objective of this step is to check the correctness of the boundary cell. Now, if the PT fails, we can use the optional *Multiple Electrodes Actuation Test (MEAT)* step to locate this error. This step named as *MEAT* here we can actuate more than one electrode simultaneously. If the error is detected, we have to bypass this faulty cell from the other step. If *MEAT* fails to detect fault in the peripheral cells, we have to halt the entire process, which is the fundamental limitation of the *MEAM*. The next step is the *RPT*, used to find out the fault in any non-peripheral cell. If *RPT* fails, there is a non-peripheral cell fault, and the MEAT step was used to diagnose this error. The method we suggest consists of four distinct steps. The peripheral test is required to ensure that the boundary cell is error-free, which is the first stage in our suggested technique. If a problem is discovered at the peripheral, the MEAT step will be used to locate the faulty cell x and add it to the faulty list F_c. For the next phase, known as *RPT*, we bypass the cells in F_c. The *RPT* will figure out the fault of the non-peripheral cells. If a fault is found, the *MEAT* step is used to determine the location of this fault. Now, every time we use the *MEAT* step, we must consider the following three options:

- **Case 1:** The stucked droplet remains undiscovered at the source after the MEAT step if the fault type is *electrodes short fault* and the fault location is along the direction of the droplet movement. As a result, the *Modified Multiple Electrodes Actuation Test (MMEAT)* step is utilized to determine the location of the issue.
- **Case 2:** If the fault is an *electrode open fault*, we can use the MEAT step to identify the exact location of the defect.
- **Case 3:** The fault is not identified in the MEAT step if the fault type is *electrodes short fault* and the fault site is orthogonal to the path of the droplet movement. As a result, *CPT* step is employed as the final step to guarantee that the biochip is free of errors.

If *MEAT* fails, the only option for locating the error is to use the *MMEAT* step. Any problem found during the *CPT* indicates that the defect is an *electrodes short fault*. As a result, the *MMEAT* step is employed to determine the exact location of the fault. The primary limitation of the MEAT method [6] is it can't diagnose the electrodes short fault. To overcome this problem, we have proposed the MEAM method. Using the MEAM method, we can diagnose the electrodes short fault. Even yet, MEAM has some basic limitations. First, we cannot use the MEAM method for any arbitrary biochip layout. It only applies to biochips that are rectangular. Second, it cannot diagnose the electrodes short fault in the peripheral. Even though we offer a solution in Section 5.5 to find electrodes short issue in peripheral. The following are all of the basic phases in this algorithm:

- **Peripheral Test (PT):** To visit all of the boundary or peripheral cells, we use two independent test droplets. Test droplets are carried in parallel; the first one visits all of the top and right peripheral border cells. The second one, on the other hand, visits all of the remaining boundary cells. If any droplet fails to reach the sink within a given time unit, a problem in the routing path is present. As a result, *MEAT* is utilized to diagnose and, in the future, bypass this defective cell. However, if *MEAT* fails to detect it, it means the problem is an electrodes short fault, and the *MEAM* algorithm must be stopped.
- **Row-wise Path Test (RPT):** This step is necessary to check *any Electrode Open Fault* in the non-peripheral cells. This step indeed identifies any Electrode Open Fault, but this is not true for *electrodes short fault*. How to detect any *Electrodes Short Fault* will be discussed in the later section. One or more test droplets are parallelly transported following a predefined routing path $rd^{i-1}r^{N-1}d^{M-i}r$. Any fault identified in the *PT step* is bypassed in this step. In the worst scenario, *MEAT* fails to diagnose the fault location and for which *MMEAT* step is used to identify this Electrodes Short Fault.
- **Multiple Electrodes Actuation Test (MEAT):** This is optional but the foremost step for fault diagnosis. If specific requirements are addressed later, we can trigger several electrodes in a single time cycle if particular conditions are met. However, we must maintain a sufficient distance between two actuated electrodes to avoid two consecutive droplets from accidentally merging. If any of the paths are faulty, the stucked droplet will bypass any non-faulty paths. All of the droplets

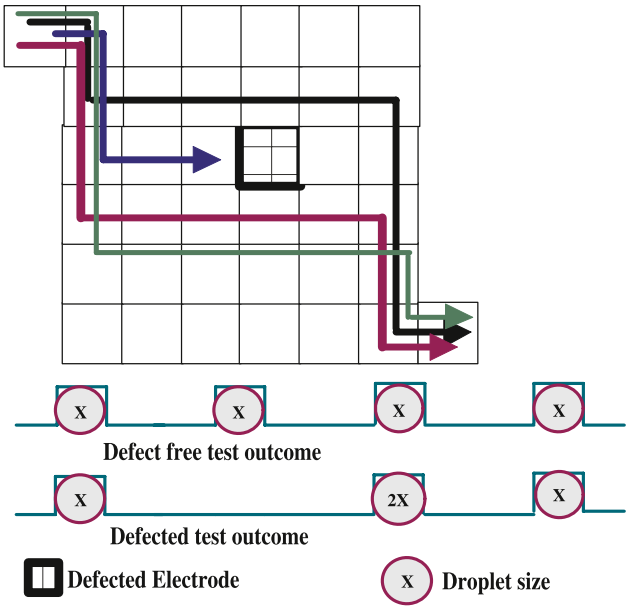

Fig. 5 Test outcome of MEAT in defect free and defected condition

identified in the sink are the same size in the fault free condition (X). If there is a problem in any path, at least one double-sized ($2X$) droplet will be identified at the sink. The test outcome of *MEAM* in the defect-free and defective condition depicted in Fig. 5. We can determine which row or column is defective using the droplet detection sequence. As a result, we deliberately send a test droplet along the problematic path and wait for the t_p time. Assume the test droplet gets stuck in path P. For each electrode $E_i \subset P$ have given a sequence number S_i where $1 < i < (length\ of\ P)$. For any two successive sequences $\{S_i, S_j\}, | S_i - S_j | = 1$. For any S_i and S_j if $S_i < S_j$ shows that E_i visited before E_j in the path P. To know the exact fault location we have to diagnose only the unvisited electrodes of P. Suppose an open fault presents at electrode E_i of P causes stuck a droplet at E_{i-1}. From here, the droplet stucked at E_{i-1} only moves towards the backward direction of P. Hence; at the 1^{st} clock cycle, we can actuate E_{i-2} to move the stucked droplet from E_{i-1} to E_{i-2}. In the 2^{nd} clock cycle, we can actuate E_{i-3} to carry the same droplet from E_{i-2} to E_{i-3}. We have to repeat the same procedure until it's detected at the source. If the droplet is detected, we can conclude that electrode E_i is a faulty electrode; otherwise, we must repeat the same procedure for the next probable erroneous position, E_{i+1}. To optimize the total number of clock cycles, we can test E_i and E_{i+1} parallelly if the following conditions are met.

- For any two consecutive electrodes E_i and E_j , if $S_i < S_j$, E_i will be tested first, followed by E_j.
- When we reach the 3^{rd} clock cycle of E_i, then simultaneously we can actuate the next probable faulty electrode E_j.

- **Modified Multiple Electrodes Actuation Test (MMEAT):** This step is optional and required when the *MEAT* step fails to identify the fault positions. *MEAT* is not suitable to identify the *electrodes short fault*. Thus we modify the *MEAT* algorithm [6] slightly to identify the *electrodes short fault*. Assume that in Fig. 6b, black shaded electrodes are electrically shorted. Hence, the test droplet gets stuck in between these two shorted electrodes. According to Algorithm 1 first, we use the *MEAT* step to identify the faulty position. However, the *MEAT* step fails to detect the fault position, which confirms the type of the fault as electrodes short fault. Thus we have to use the *MMEAT* step to know the exact position of the electrodes short fault. Suppose that the test droplet stucked at the J^{th} path, then we can use any consecutive K^{th} path, which is detected as fault-free in its previous step and is also closest to the source. Hence, the actual fault exists in the J^{th} path; thus, in this litera-

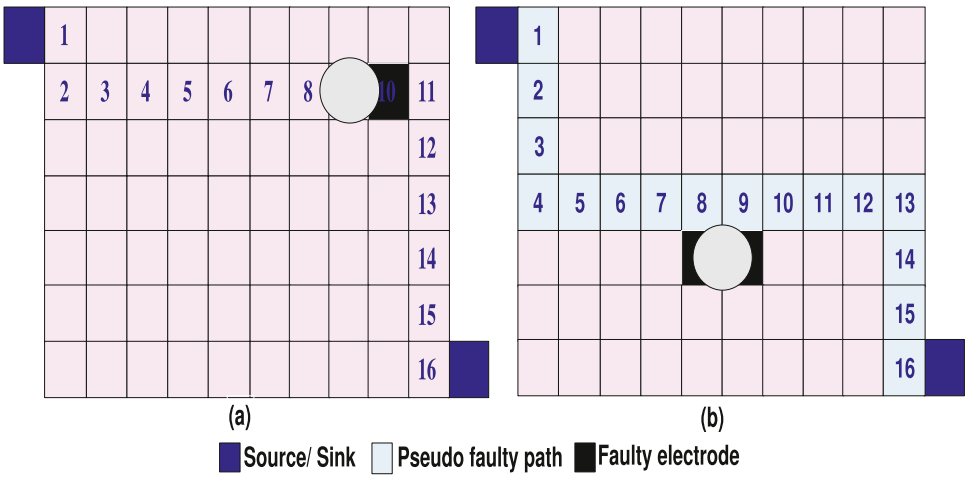

Fig. 6 **a** Droplet get stuck due to Electrode Open Fault, **b** Droplet get stuck due to Electrodes Short Fault

ture, the K^{th} path is termed as the *pseudo-faulty path*. As we are actuating one or more electrodes of the pseudo-faulty path, then any droplet stucked at the J^{th} path will move to the pseudo-faulty path. Now, we have to apply the *MEAT* step at the pseudo-faulty path.

- **Column-wise Path Test (CPT):** We know that if there is a *Electrodes Short fault* orthogonal to the droplet's routing path, the *RPT step* will not able to detect it. Hence, to check a biochip is completely fault-free or not, we need this step. Here, one or more test droplets are parallelly transported in using a predefined routing path $r^{N-i+1}d^{M-1}r^{i}$, where $1 < i < n$. Now if any fault identified in this step certainly *Electrodes Short Fault* which is diagnosed using *MMEAT* step. Here we also give two illustrative examples to explain our proposed method.

Example 1 Suppose an open fault exists at which a droplet gets stuck at electrode 9 of any biochip of size 7×10 shown in Fig. 6a. Assume that *PT* step ran successfully. Due to this open fault a test droplet of *Row 2* stucked at *RPT* step which is shown in Fig. 6a. Thus, we have to identify this fault location using *MEAT* step. Complete actuation sequence with the clock cycles has been shown in the Table 3. As we assumed that *PT* ran successfully, then the fault certainly exists in any of the electrodes between 3 to 10 in Fig. 6a. Hence the droplet may be stucked at any electrode's position between 2 to 9. So, in the first clock cycle, we actuate electrode 1. If there is any droplet stucked at electrode 2 will move to electrode 1 for detection. As nothing was detected, we can say electrode 3 is non-faulty. Let us check the next probable faulty position, which is electrode 4. Now, see Table 3 as per the rule mentioned above we have tested electrode 4 and 5 simultaneously at the 6^{th} clock cycle. Similarly, we can repeat the *MEAT* step for other electrodes and finally get that electrode 10 is faulty. Now, we can use the same test droplet to visit the remaining unvisited cells bypassing electrode 10. This bypass process also helps you to determine the other undetected fault within the same path.

Table 3 Detection of the Stucked droplet due to Electrode Open Fault in a 7×10 biochip

CC	AESN	Status of Droplet Detection at source	Conclusion
1	1	Not detected	No fault present in Electrode 3
2	2	Not detected	Indecisive
3	1	Not detected	No fault present in Electrode 4
4	3	Not detected	Indecisive
5	2	Not detected	Indecisive
6	1, 4	Not detected	No fault present in Electrode 5
7	3	Not detected	Indecisive
8	2, 5	Not detected	Indecisive
9	1, 4	Not detected	No fault present in Electrode 6
10	3, 6	Not detected	Indecisive
11	2, 5	Not detected	Indecisive
12	1, 4, 7	Not detected	No fault present in Electrode 7
13	3, 6	Not detected	Indecisive
14	2, 5, 8	Not detected	Indecisive
15	1, 4, 7	Not detected	No fault present in Electrode 8
16	3, 6	Not detected	Indecisive
17	2, 5	Not detected	Indecisive
18	1 ,4, 7	Not detected	No fault present in Electrode 9
19	3	Not detected	Indecisive
20	2	Not detected	Indecisive
21	1	Detected	Fault present in Electrode 10

CC clock cycle, *AESN* actuated electrode sequence number

Example 2 Consider the biochip in Fig. 6b with a droplet stuck between two electrode positions (5, 5) and (5, 6) due to the electrodes short fault. Assume the peripheral test was completed successfully. After that, we must do the *RPT* step, but the droplet in row 5 is not detected at the sink. Hence, a fault exists row 5. However, we discussed earlier that the stucked test droplet might be bypassed throw row 4. Hence we deliberately inject a test droplet at row 5 and wait for the required number of time cycles so that the test droplet gets stuck at the faulty position. Now we must do the MEAT step under the assumption that the fault is an *electrode open fault* since nothing is detected in the *MEAT* step, which can infer that the type of fault is *electrodes short fault*. Hence we apply the *MMEAT* step to know the shorted electrodes. In the *MMEAT* we actuate the electrodes of the pseudo faulty path so that the stucked droplet may be bypassed through this path. Table 4 shows all of the actuation steps along with the clock cycles. If the peripheral test is successful, a fault can be found in any pair of two consecutive electrodes beneath the pseudo-faulty path. So, the droplet may be stuck in between any pair of two consecutive electrodes shown in Fig. 6b. Thus, we actuate electrode 4 on the first clock cycle, then electrode 3 and electrode 2 on the subsequent clock cycles. We can actuate electrodes 2 and 5 at the same clock cycles. In the next clock cycle, we can actuate electrodes 1 and 4 in the same way. If the droplet became stuck between the pair of electrodes underneath electrodes 4 and 5, it transported to electrode 1 and was detected by the source's sensing circuit. However, nothing is detected, which means that the fault exists in any other pair of electrodes, which is shown as the shaded electrodes in Fig. 6b. According to the actuation rule, we have already started testing the next probable faulty pair underneath the electrodes pair of electrode 5 and electrode 6. We actuate more than one electrode at the same clock cycle, which will automatically reduce total test time. In this way, we repeat the *MMEAT* for other electrodes till we detect the faulty positions. The test droplet was identified at the source

Table 4 Detection of the Stucked droplet due to Electrodes Short Fault in a 7×10 biochip

CC	AESN	Status of Droplet Detection at source	Conclusion
1	4	Not detected	Indecisive
2	3	Not detected	Indecisive
3	2, 5	Not detected	Indecisive
4	1, 4	Not detected	Electrode underneath of the electrode 4 is Non Faulty
5	3, 6	Not detected	Indecisive
6	2, 5	Not detected	Indecisive
7	1, 4, 7	Not detected	Electrode underneath of the electrode 5 is Non Faulty
8	3, 6	Not detected	Indecisive
9	2, 5, 8	Not detected	Indecisive
10	1, 4, 7	Not detected	Electrode underneath of the electrode 6 is Non Faulty
11	3, 6	Not detected	Indecisive
12	2, 5	Not detected	Indecisive
13	1, 4	Not detected	Electrode underneath of the electrode 7 is Non Faulty
14	3	Not detected	Indecisive
15	2	Not detected	Indecisive
16	1	Detected	Short fault exists in the pair of electrodes beneath electrodes 8 and 9

CC clock cycle, *AESN* actuated electrode sequence number

at the 16^{th} clock cycle, as shown in Table 4. We can deduce that the electrodes' short fault exists in the pair of electrodes beneath electrodes 8 and 9. We can use the same test droplet to visit the remaining unvisited cells bypassing the detected faulty pair. This bypass process helps us to determine the other undetected fault within the same path.

Algorithm 1 Algorithm MEAM

Require: A Biochip of size $M \times N$
Ensure: Faulty Set F_c

$F_c \leftarrow \emptyset$
if PT crash **then**
  do $MEAT$ to diagnose the faulty location and append to F_c
  if $MEAT$ fails **then**
    Then the fault is electrodes short fault and not diagnosable using $MEAM$
    Return
  end if
  Bypass all the faulty cells in F_c for the next step
end if
for all Unvisited path p as row-wise **do**
  do RPT
  if any p fails in RPT **then**
    do $MEAT$ to diagnose the faulty location and append to F_c
    if $MEAT$ fails to identify the faulty location f **then**
      Do $MMEAT$ to diagnose the faulty location and append to F_c
    end if
  end if
end for
for all Unvisited path p as column-wise **do**
  do CPT
  if any p fails in CPT **then**
    p contains electrodes short fault and do $MMEAT$ to diagnose the faulty locations
    Append those faulty locations to F_c
  end if
end for

5.1 Testing Time for Single Fault

Using our proposed method *MEAM*, we calculate the overall test time in offline mode for a biochip of size $(M \times N)$. All of the biochip cells are accessible in the offline testing mode. To determine the chip's condition, we do the first two steps *(PT and RPT)*. To calculate the overall test time (T), we need to know how many cells each droplet has covered. If Q is the number of cells in the path, then $Q-1$ is the number of time cycles required to get from the source to the destination. All of the droplets in MEAT covered the same number of cells, hence $Q = M + N$. We knew that at least 3 time cycles are required to avoid merging between two consecutive droplets. Hence the time taken up to the *Peripheral Step* is $T_1 = M + N + 3$. In the *RPT Step*, $M-2$ test droplets are utilised in total. Thus the required testing time in *RPT Step* is $T_2 = (M+N) + 3((M-2)-1) = 4M + N - 9$. Hence the time taken up to the RPT step is $T_{Open} = T_1 + T_2 = 5M + 2N - 6$. However, if the electrodes short fault is orthogonal to the droplet routing path, it is possible that it will go undetected. Hence, for the electrodes short fault detection, the CPT step is recommended. In the *CPT step*, $N-2$ test droplets are utilized in total.. Thus the required testing time in *CPT Step* is $T_3 = (M+N) + 3((N-2)-1) = M + 4N - 9$. Hence the total testing time $T = T_{Open} + T_3 = 6M + 6N - 15$.

5.2 Diagnosis Time for Single Fault

Two types of defects must be diagnosed: electrode open fault and electrodes short fault. First, I'll talk about how long it takes to diagnose an electrode open defect on any $M \times N$ biochip. Let, the open fault is present in any non-peripheral cell and the fault position is (x_e, y_e), where $1 < x_e < M$ and $1 < y_e < N$. For peripheral cells, we need special care so I am ignoring it now. Suppose the open fault is identified during the *RPT step*. We know the row number that is x_e but y_e is unknown. The droplet stuked in (x_e, y_{e-1}) bypass through its consecutive row. So we purposefully send a test droplet through the faulty path and it will definitely stuck at $(x_e, y_{e-1}) \subset$ *non peripheral cells*. The number of non-peripheral cells in this faulty path is $N-2$. So, we halt the the *MEAT step* for $(x_e + N - 2 + 1) = x_e + N - 1$ clock cycles which is also known as test droplet insertion time (Td_{it}). If $x_e > 2$ then the droplet is detected after $(x_e - 1) + 3(y_e - 2) = x_e + 3y_e - 7$. But when $x_e = 2$ then the first probable fault is detected at the first clock cycle, so the required clock cycles are $x_e + 3y_e - 8$. So the total diagnosis time (Dt) can be summarized as follows,

$$Dt = \begin{cases} x_e + 3y_e - 7 + Td_{it} & 2 < x_e \leq N \\ x_e + 3y_e - 8 + Td_{it} & \text{Otherwise} \end{cases}$$

Now, if the *MEAT* step is applied after the *CPT* step, we need to change the above equation slightly. In this equation, we have to exchange x_e and y_e. In the case of the droplet, insertion time replaces N by M. Now for electrodes short fault, we have to apply the *MEAT* step first, and when the test droplet is not detected, we apply the *MMEAT* step. The *MMEAT* step takes an equal amount of time as the *MEAT* step. So, the required test time for a single short fault is twice Dt or $2Dt$.

5.3 Multiple Fault Testing and Diagnosis

After identifying that a single fault exists in the faulty path, we have to bypass this faulty cell (s) to check the remaining unvisited cells. For multiple fault identification, two scenarios might be happening. In the first scenario, multiple faults may exist in the same row. Hence, for multiple fault identification, we have to bypass the first faulty position. So, to bypass the first faulty location, we need to cover total $(Q) = M + N + 1 + 2 = M + N + 3$ cells. If Q is the number of cells in this path, then the required number of time cycles to reach the destination from the source is $Q - 1 = M + N + 2$. Thus to identify the following K number of faults that exist in the same row, we have needed total $\sum_{i=1}^{K}(M + N + 2i) = K(M + N + K + 1)$ clock cycles. In the second scenario, assuming that the next K faults have been distributed on the different rows, we need a total of $K(M + N + 2)$ clock cycles. Hence to diagnosis the following K number of faults, the incurred diagnosis time should be $(Td_{it} + 2) + Dt$. It is the required testing and diagnosis time when the fault is identified in the *RPT* step. However, if the fault is identified in the *CPT* step, we can use similar techniques to know the incurred testing and diagnosis time. We have already seen that the *MMEAT* step takes twice the required testing and diagnosis time as in the *MEAT* step. Thus multiple electrodes' short fault testing and diagnosis time take twice the same number of open fault's detection time.

5.4 Online Testing

Some of the connected cells may not be available for testing during concurrent testing. This cluster of cells is cooperating to carry out certain important biochemical processes. Because they are not available for testing, we can consider this group of connected cells an "obstacle". Using the method [23] all the bioassay operations for DMFB is scheduled is known as a priori. We can append these blocked cells in F_c. Now, as shown in Fig. 7, we can design a path to bypass those cells in *Faulty Set (F)*. Now, if any cell is not available for testing, we have to stall a few clock cycles until their availability. We have already calculated the required testing time (T) of any $M \times N$ biochip in offline mode. Hence, the total testing for online testing is equal to the summation of actual time (T) and the total waiting time.

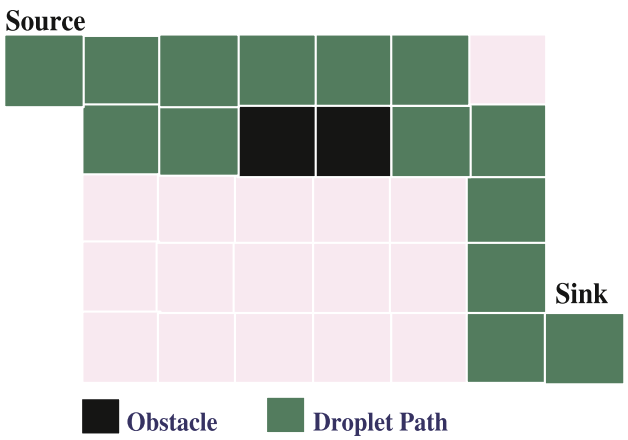

Fig. 7 Online Testing of the biochip

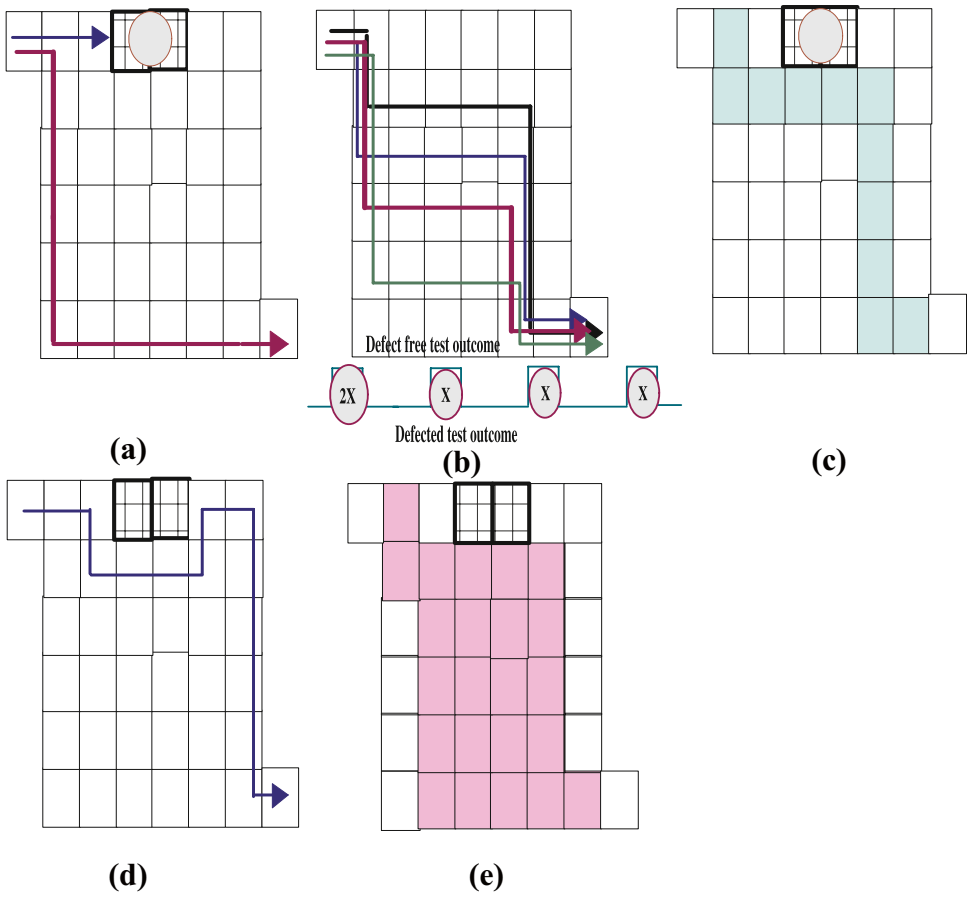

Fig. 8 **a** Electrodes short fault in the peripheral, **b** Use RPT step and defected test outcome was detected, **c** Pseudo-faulty path for defective peripheral, **d** Bypass faulty cell(s) to visit other unvisited cell, **e** Use CPT step to locate other fault

5.5 A Solution to Identify Electrodes Short Fault in the Peripherals

We cannot use the *MEAM* directly to diagnose electrodes short fault in the peripherals. However, if we slightly change *MEAM*, we can use it to handle this particular case. Suppose there is a short fault in the peripheral, shown in Fig. 8a. If the peripheral test fails, we do the *MEAT* step to identify this fault location. However, *MEAT* fails to locate this error. It means that the type of fault is a short fault. So, instead of using MMEAT, we use the *RPT* step for other unvisited cells, shown in Fig. 8b. Assume that *RPT* ran successfully, so we can use the row adjacent to faulty peripheral as a pseudo path, shown in Fig. 8c. We have to inject a test droplet in the faulty peripheral purposefully. Now, we can use the *MMEAT* step to locate this faulty position. We can use the same test droplet to visit the remaining unvisited cells bypassing the detected faulty pair, which is shown in Fig. 8d. Finally, we use the *CPT* step to like Fig. 8e to determine any other electrode short fault in the biochip. So, this is a comprehensive solution to handle the electrodes' short fault in the peripherals.

6 Simulation Result

Our algorithm is implemented using C language, with the system having 4 GB RAM and Core 2 Duo with processor speed 2.4 GHz. Here, we compared our method to the algorithms presented in [5, 24, 26]. We can move a droplet to the next cell in *62.5 ms*, which is equivalent to the time slot

Table 5 Comparison of diagnosis time between MEAM and ITM [5]

M × N	DT of MEAM	DT of ITM [5]	% Imp of DT
5 × 5	1.4375	1.625	11.54
5 × 6	1.5625	1.875	16.67
6 × 6	1.6875	2.3125	27.03
6 × 7	1.6875	2.5	32.5
7 × 7	1.9375	2.8125	31.11
7 × 8	2.5625	3	14.58
8 × 8	2.9375	3.5625	17.54
8 × 9	3.125	3.5	10.71
9 × 9	3.375	4.125	18.18
9 × 10	3.4375	4.25	19.12
10 × 10	3.625	4.4375	18.31

Average improvement of diagnosis time ≈ 20.59%. Average diagnosis time ≈ 18.31%

Table 6 Comparison of diagnosis time between MEAM and ITM [5] for multiple faults diagnosis

M×N	Average Multiple Faults Diagnosis Time in Total Number Steps					
	Single Fault		Double Faults		Triple Faults	
	MEAM	ITM	MEAM	ITM	MEAM	ITM
7 × 8	41	48	85	101	125	147
8 × 9	50	56	93	115	137	196
9 × 10	55	68	106	120	157	216
10 × 10	58	71	116	152	180	275

length, using a *50 V* actuation voltage and a switching frequency of *16 Hz* [21]. In Table 5 we have compared the diagnosis time of *MEAM* with the proposed algorithm *ITM* [5]. The rectangular biochip size ranges from 5 × 5 to 480 × 640, as shown in column 1. The next two columns represent the diagnosis time (*DT*) of MEAM and the *ITM*, respectively. The last column shows the average improvement of diagnosis time compared to *ITM*. The diagnosis time (*DT*) in CPU time and the average improvement (*%Imp*) are shows in percentage. From this Table 5, it is evident that our proposed algorithm's diagnosis time is much better compared to *ITM*. It is also observed that the performance of *MEAM* also improving with the increasing chip size. For the chip size 480 × 640 to diagnosis, a single fault *MEAM* takes only 325 sec. compared to 11452 sec. (approx.) in case of *ITM*. On average, *MMEAT* takes 2.49 sec. to diagnose a single fault.

MEAM's testing time is less than the other methods provided in [24, 26], as shown in Fig. 9. In Fig. 10 we compare the average diagnosis time of *MEAM* with *Euler Path Based* method [24] and *ITM* [5]. Figure 10 shows that the diagnosis time of *MEAM* is much better than the method based on the *Euler path*. Now, *MEAM* can diagnose multiple faults, so its diagnosis time is compared with the diagnosis time of *ITM* [5]. Multiple fault diagnosis is another crucial aspect of *MEAM*. From Table 6 it's clear that we can diagnose

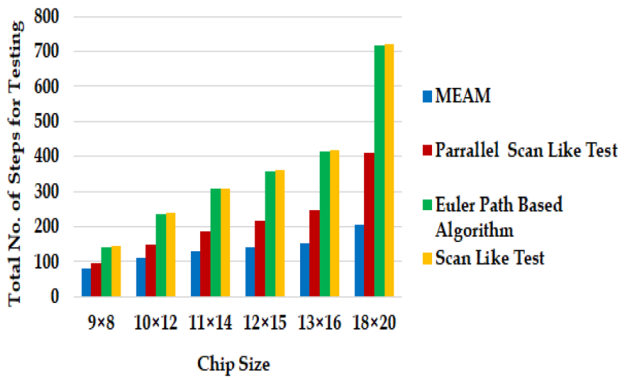

Fig. 9 MEAM is compared with Parallel Scan Method (PSL) [26], Scan Path-based Method (SP) [26] and Euler path based algorithm [24]

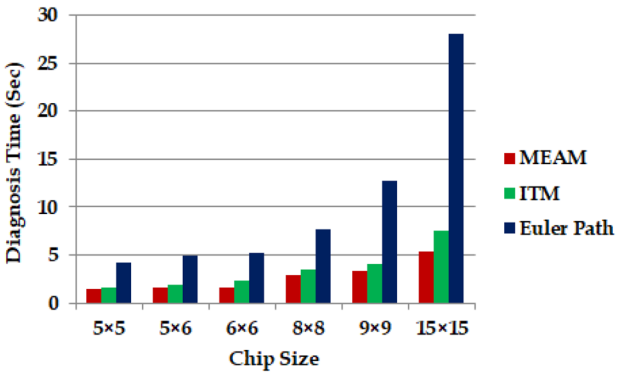

Fig. 10 Average Diagnosis Time of *MEAM* is compared with *ITM* [5] and Euler path based algorithm [24]

multiple short faults within very less time, and the result also compared to *ITM* [5]. Electrodes short fault identification within a short time is another challenging task to perform. Our proposed method can also detect electrodes short fault and the total testing and diagnosis time is just twice the same number of open faults detection time shown in Section 5.3. The other literature has no data regarding the electrodes short fault, so we cannot compare it directly. Hence, we can conclude that our proposed algorithm is time efficient and robust to detect electrode open fault and electrodes short fault compared to the other algorithms reported in the different kinds of literature.

7 Conclusion

This paper proposed a heuristic technique for reducing the testing time of *DMFBs* with regular shapes. The *MEAT* step is used to diagnose an open electrode fault in this case. However, if the defect is an electrodes short fault, it may fail to detect it. As a result, we used the *MMEAT* step to detect the electrodes short fault. Here we use the testing and diagnosis steps interchangeably, which reduces the incurred testing and diagnosis time. Furthermore, we test with multiple test droplets, which cuts down on overall testing time. We only use one test droplet for diagnosis, which is also cost-effective.

Funding The authors did not receive any funding to conduct this research.

Data Availability For Fig. 9, data generated or analyzed during this study are included based on the following published articles

1. Paper Name: Parallel Scan-Like Test and Multiple-Defect Diagnosis for Digital Microfluidic Biochips
   - Author(s) Name: Tao Xu and Krishnendu Chakrabarty
   - DOI: https://doi.org/10.1109/TBCAS.2007.909025
2. Paper Name: Testing and diagnosis of realistic defects in digital microfluidic biochips

- Author(s) Name: Fei Su and William Hwang and Arindam Mukherjee and Krishnendu Chakrabarty
- DOI: https://doi.org/10.1007/s10836-006-0554-8

For Fig. 10, data generated or analyzed during this study are included based on the following published article,

1. Paper Name: Iterative Parallel Test to Detect and Diagnose Multiple Defects for Digital Microfluidic Biochip
- Author(s) Name: Sourav Ghosh, Dolan Maity, Arijit Chowdhury, Surajit Kumar Roy and Chandan Giri
- DOI: https://doi.org/10.1109/ATS47505.2019.00027
2. Paper Name: Testing and diagnosis of realistic defects in digital microfluidic biochips
- Author(s) Name: Fei Su and William Hwang and Arindam Mukherjee and Krishnendu Chakrabarty
- DOI: https://doi.org/10.1007/s10836-006-0554-8

For Tables 5 and 6, data has been taken from the following paper,

1. Paper Name: Iterative Parallel Test to Detect and Diagnose Multiple Defects for Digital Microfluidic Biochip
- Author(s) Name: Sourav Ghosh, Dolan Maity, Arijit Chowdhury, Surajit Kumar Roy and Chandan Giri
- DOI: https://doi.org/10.1109/ATS47505.2019.00027

For analysis purposes, we have generated some data using our proposed method, and on request, the source code can be available from the corresponding authors.

Declarations

Conflict of Interest The authors did not receive support from any organization for the submitted work. No funding was received to assist with the preparation of this manuscript. No funding was received for conducting this study. No funds, grants, or other support was received. The authors declare that they have no competing interests.

References

1. Datta S, Joshi B, Ravindran A, Mukherjee A (2009) Efficient parallel testing and diagnosis of digital microfluidic biochips. ACM J Emerg Technol Comput Syst (JETC) 5(2):10
2. Dinh TA, Yamashita S, Ho TY, Chakrabarty K (2015) A general testing method for digital microfluidic biochips under physical constraints. In: Proceedings of IEEE International Test Conference (ITC), IEEE, pp 1–8
3. Fair RB (2007) Digital microfluidics: is a true lab-on-a-chip possible? Microfluid Nanofluid 3(3):245–281
4. Ghosh S, Rahaman H, Giri C (2018) Optimized concurrent testing of digital microfluidic biochips. In: Proceedings of the 31st International Conference on VLSI Design and 17th International Conference on Embedded Systems (VLSID), IEEE, pp 453–454
5. Ghosh S, Maity D, Chowdhury A, Roy SK, Giri C (2019) Iterative parallel test to detect and diagnose multiple defects for digital microfluidic biochip. In: Proceedings of the IEEE 28th Asian Test Symposium (ATS), pp 147–1475
6. Ghosh S, Maity D, Chowdhury A, Roy SK, Giri C (2020) Efficient fault detection and diagnosis of digital microfluidic biochip using multiple electrodes actuation. In: Proceedings of the IEEE International Test Conference India, IEEE, pp 1–4
7. Huang X, Xu C, Zhang L (2020) An efficient algorithm for optimizing the test path of digital microfluidic biochips. J Electron Test 36(2):205–218
8. Jokerst NM, Luan L, Palit S, Royal M, Dhar S, Brooke M, Tyler T II (2009) Progress in chip-scale photonic sensing. IEEE Trans Biomed Circuits Syst 3(4):202–211
9. Li Z, Dinh TA, Ho TY, Chakrabarty K (2014) Reliability-driven pipelined scan-like testing of digital microfluidic biochips. In: Proceedings of the IEEE 23rd Asian Test Symposium, pp 57–62
10. Li Z, Lai KYT, Yu PH, Chakrabarty K, Ho TY, Lee CY (2016) Built-in self-test for micro-electrode-dot-array digital microfluidic biochips. In: Proceedings of the IEEE International Test Conference (ITC), IEEE, pp 1–10
11. Libao D, Ning S, Tao R, Ning F (2017) A serial structure for digital microfluidic biochips online testing. In: Proceedings of the 13th IEEE International Conference on Electronic Measurement & Instruments (ICEMI), IEEE, pp 229–235
12. Mitra D, Ghoshal S, Rahaman H, Bhattacharya BB, Majumder DD, Chakrabarty K (2008) Accelerated functional testing of digital microfluidic biochips. In: Proceedings of the 17th Asian Test Symposium, pp 295–300
13. Paşaniuc B, Garfinkel R, Măndoiu I, Zelikovsky A (2011) Optimal testing of digital microfluidic biochips. INFORMS J Comput 23(4):518–529
14. Pollack MG (2001) Electrowetting-based microactuation of droplets for digital microfluidics. Duke University, Durham, NC, USA
15. Schasfoort RB, Schlautmann S, Hendrikse J, Van Den Berg A (1999) Field-effect flow control for microfabricated fluidic networks. Science 286(5441):942–945
16. Shin YJ, Lee JB (2010) Machine vision for digital microfluidics. Rev Sci Instrum 81(1):014302
17. Shukla V, Hussin FA, Hamid NH, Ali NBZ, Chakrabarty K (2017) Offline error detection in meda-based digital microfluidic biochips using oscillation-based testing methodology. J Electron Test 33(5):621–635
18. Srinivasan V, Pamula VK, Fair RB (2004) An integrated digital microfluidic lab-on-a-chip for clinical diagnostics on human physiological fluids. Lab Chip 4(4):310–315
19. Su F, Ozev S, Chakrabarty K (2003) Testing of droplet-based microelectrofluidic systems. In: Proceedings of the International Test Conference, IEEE, pp 1192–1200
20. Su F, Ozev S, Chakrabarty K (2004) Concurrent testing of droplet-based microfluidic systems for multiplexed biomedical assays. In: Proceedings of the International Conference on Test, IEEE, pp 883–892
21. Su F, Hwang W, Mukherjee A, Chakrabarty K (2005) Defect-oriented testing and diagnosis of digital microfluidics-based biochips. In: Proceedings of the IEEE International Conference on Test, Nagoya, Japan, p 10
22. Su F, Ozev S, Chakrabarty K (2005) Ensuring the operational health of droplet-based microelectrofluidic biosensor systems. IEEE Sens J 5(4):763–773
23. Su F, Ozev S, Chakrabarty K (2006) Test planning and test resource optimization for droplet-based microfluidic systems. J Electron Test 22(2):199–210
24. Su F, Hwang W, Mukherjee A, Chakrabarty K (2007) Testing and diagnosis of realistic defects in digital microfluidic biochips. J Electron Test 23(2–3):219–233
25. Verpoorte E, De Rooij NF (2003) Microfluidics meets mems. Proc IEEE 91(6):930–953
26. Xu T, Chakrabarty K (2007) Parallel scan-like test and multiple-defect diagnosis for digital microfluidic biochips. IEEE Trans Biomed Circuits Syst 1(2):148–158
27. Zhang T, Chakrabarty K, Fair RB (2018) Microelectrofluidic systems: Modeling and simulation. CRC Press
28. Zheng W, Yu H, Feng L, Fu P, Jiang H (2017) Single droplet online testing path optimization for digital microfluidic biochips based on the improved ant colony algorithm. In: Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC), IEEE, pp 1–6
29. Zhong Z, Chakrabarty K (2019) Fault recovery in micro-electrode-dot-array digital microfluidic biochips using an ijtag

networkbehaviors. In: Proceedings of the IEEE International Test Conference (ITC), IEEE, pp 1–10
30. Zhong Z, Li Z, Chakrabarty K, Ho TY, Lee CY (2018) Microelectrode-dot-array digital microfluidic biochips: Technology, design automation, and test techniques. IEEE Trans Biomed Circuits Syst 13(2):292–313
31. Zhong Z, Zhu H, Zhang P, Morizio J, Huang TJ, Chakrabarty K (2019) Hardware design and experimental demonstrations for digital acoustofluidic biochips. In: Proceedings of the IEEE Biomedical circuits and systems conference (BioCAS), IEEE, pp 1–4

Sourav Ghosh completed his B.Tech. in IT from University of Kalyani and M.E from Bengal Engineering & Science University, Shibpur, India. Currently, he is working as an Assistant Professor in IEM and also doing his Ph.D. from Indian Institute of Engineering Science and Technology under the guidance of Prof. Chandan Giri on Biochip Testing. His areas of interest are Image Steganography, 3D SoC Testing and Biochip Testing.

Surajit Kumar Roy is currently an Associate Professor in the Department of Information Technology, Indian Institute of Engineering Science and Technology, Shibpur, India. He received the B.Sc. (Hons. in Physics) from Calcutta University, India. He also received a Bachelor of Technology in computer science and engineering and subsequently a Master of Technology in computer science and engineering from Calcutta University, India in 2002 and 2004. He was awarded a Ph.D. degree from the Indian Institute of Engineering Science and Technology (IIEST), Shibpur. His research interest includes VLSI testing, 3D Integrated Circuits, TSV testing and recovery Embedded Systems, and Hardware security. He was a recipient of the Best Ph.D. Thesis Award at ATS16. He has contributed several research articles in peer-reviewed international journals and conferences.

Chandan Giri received B.Tech. degree in Computer Science & Engineering from Calcutta University, Kolkata, India in 2002 and subsequently Masters of Engineering (M.E.) in Computer Science & Engineering from Jadavpur University, Kolkata, India in 2002 and the Ph.D. degree from the Department of Electronics & Electrical Communication Engineering, Indian Institute of Technology, Kharagpur in 2008. He served as a Lecturer at the College of Engineering and Management, Kolaghat from 2002 to 2005. He served as an Assistant Professor in the Department of Information Technology, Indian Institute of Engineering Science and Technology, Shibpur, India, from 2008 to 2018. He is currently serving as an Associate Professor in the Department of Information Technology, Indian Institute of Engineering Science and Technology, Shibpur, India. His research interests are Wireless Sensor Networks, testing and design-for testability of integrated circuits (especially 3D and multicore chips), and Microfluidic Biochip Design and Test. He served as a Conference/Symposium Co-Chair in many IEEE international conferences such as VLSI Design, VLSI Design and Test (VDAT), ISED, ISDCS, RC, etc.. He is a member of IEEE and ACM.