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Pareto optimization technique in actuation control for error minimization and reliability analysis in an operational pin-constrained digital microfluidic biochip

Subhamita Mukherjee[a,*], Indrajit Pan[b], Tuhina Samanta[c]

[a] Techno India, Salt Lake, Kolkata, India
[b] RCC Institute of Information Technology, Kolkata, India
[c] Indian Institute of Engineering Science and Technology, Shibpur, India

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ABSTRACT

Droplet routing in digital microfluidic biochip (DMFB) attempts to reduce overall droplet routing time. This phenomena increases repeated use of electrodes during electro-wetting on dielectrics (EWOD). Repeated use of same electrode requires frequent actuation. Often, this over utilization and frequent actuation of same electrodes affects the reliability of DMFB since these electrodes become fault prone under excessive use. Research on fault probability reduction, fault identification and fault management are key issues to achieve reliable output from DMFB. In this paper, a fault management process is focused with the objective to gain reliable performance of DMFB. This method reduces error probabilities of DMFB through a balanced utilization and actuation of electrodes. Initial phase of the proposed work captures the utilization of different electrodes resulting from a pin-constrained droplet routing schedule of DMFB. This initial routing schedule is then reviewed to ensure equitable utilization of electrodes. This will also increase the life-span of electrodes. Consequently, that will lessen fault probability and improve reliability. Finally a Pareto optimal analysis is performed upon the data acquired from previous two processes. These studies have been experimented upon different benchmark samples including in-vitro test suites and complex assay samples like Bradford protein assay, qPCR, sucrose gradient analysis to test its robustness and the results are really encouraging.

1. Introduction

DIGITAL microfluidic biochip is a collection of multiple electrodes arranged on a two-dimensional array, which are capable of performing droplet movements based on EWOD [7,16]. In a DMFB, many droplets are routed from the source to the target location in a parallel sequence to derive a pathological result according to bioassay protocols [12]. Apart from pathological analysis, there are many other applications [12]. Objectives of this droplet routing mainly confine within minimum electrode usage and minimum routing completion time or latest arrival time [28]. In pin-constrained droplet routing technique for DMFB, minimization of the use of actuation pin is another objective. Pins are normally designated for unambiguous addressing of electrode. In pin-constrained routing process allotment of addressing pins is a critical issue. Droplet routing schedules are further optimized to reduce the numbers of pin required to complete the routing schedule [27]. Many heuristic, meta-heuristic and numerical techniques are available in literature with different routing techniques following those major objectives [12].

DMFB faces many types of defect [31]. One of those defects occurs due to dielectric breakdown resulting from application of excessive actuation voltage. Actuation of any electrode for longer duration of time causes defects due to irreversible charge concentration on an electrode. Sometimes excessive mechanical force is applied on a chip and that causes misalignment of parallel plates [29]. Sometimes it is observed that an unbalanced coating can cause non-uniform dielectric layer. Abnormal metal layer or etching variation during fabrication can also cause grounding failure or broken connections [2 and 32]. All these defects affect electrode functions and gradually that leads to erroneous output. Some of these defective electrodes no longer remain active to participate in droplet routing [33].

In a EWOD-based DMFB, frequent use of some electrodes keeps them under prolonged actuation. This over actuation results in electrode degradation. Even some electrodes remain under actuation through native bias voltage during EWOD though those are not actually used for routing [19]. This fault type is known as oversensitivity or insensitivity in capacitive sensing [13,14]. As a whole it creates

* Corresponding author.
E-mail addresses: subhamita.mukherjee@gmail.com (S. Mukherjee), p.indrajit@gmail.com (I. Pan), tuhina_samanta@yahoo.com (T. Samanta).

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reliability challenges and a need to design a mechanism for fault prone device handling.

This proposed work mainly focuses on enhancing performance reliability of DMFB through even distribution of electrode actuation.

1.1. Actuation rate

It indicates the frequency of actuation/ activation of an electrode during a bioassay operation. Actuation rate is measured through a ratio between numbers of times an electrode is actuated/ activated to the overall droplet routing time of a bioassay protocol [4].

1.2. Reliability

Reliability of DMFB is defined as the correctness in properly completing bioassay operations which are scheduled through a protocol [21].

1.2.1. Motivation

Studies show that excessive reuse of electrodes and over activation by external bias causes degradation of dielectric layer in DMFB [6,16]. This increases the potential of meeting faults. The present work attempts to deliver a more robust pin-constrained droplet routing schedule through balanced utilization of electrodes to prevent over utilization of electrodes. In the first phase, a pin constrained droplet routing schedule is derived through optimal trade-off of three parameters, (i) minimization of routing completion time (ii) minimization of pin count and (iii) minimization of reuse of different electrodes. The approach has increased the durability of electrodes. Finally the obtained result is cross-checked through a Pareto optimal analysis, which ascertains the feasibility of obtained solution.

In the remaining part of this paper, Section 2 discusses prior researches on fault detection and diagnosis in DMFB. Different droplet routing and electrode activation constraints are discussed in Section 3. A brief introduction on Pareto optimality is given in Section 4. The proposed method with discussion on pseudo code is given in Section 5; this is followed by experimental results and discussion in Section 6. Finally, the paper concludes in Section 7 with possible future directives.

2. Literature survey

2.1. Impact of multiple parameters in biochip reconfiguration

Modelling of repetitive execution of on-chip biochemical experiments in terms of cyber physical system implementation of digital microfluidic biochip was proposed in [27,31]. Main objective of cyber physical approach is to extend software centric assistance towards reconfiguration of biochip on the basis of real time feedback. Mostly the on-chip sensors take the responsibility to yield these real time feedbacks for the software.

In [19], a multi-objective optimization algorithm has been proposed which simultaneously minimizes several resources during bioassay operations in a digital microfluidic biochip. Authors have designed a progressive droplet routing as a constrained multi-objective optimization problem to address three objective functions as electrode usages, latest arrival time, and control pin allocation. A composite objective function is constructed by a weighted sum of the first two objective functions. This composite function is minimized pertaining to an upper bound on the third objective function, control pin allocation. An optimal pin-count design scheme for digital microfluidic biochips has been cited in [22]. The method integrates a very simple combinational logic circuit within the original chip. This proposed scheme can provide high throughput for bioassays with minimum number of control pins. Another pin-count minimization technique for cross-referencing DMFB has been presented in [17]. This algorithm can simultaneously optimize routing and control pin assignment. These pin constrained design issues have a large impact on the performance of the DMFB because undesirable activation of electrodes and complex pin assignment can raise potential performance issues on DMFB.

The reliability aspect of DMFB from the part of efficient pin assignment is not comprehensively addressed in the literature.

2.2. Pin constrained design issues of biochip

A work in [1], introduces a new concept of field programmable pin count aware digital microfluidic biochip. The author says the assay operations are cheaper and easier in compare to general purpose direct addressing based digital microfluidic biochip. Another work in [11], addresses both pin count minimization and obstacle avoidance aware droplet routing in electrowetting based operational digital microfluidic biochip. These obstacles are resultant of on chip embedded components. An effective integer linear programming solution was applied to achieve high routability and less complex design. Electrowetting-on-dielectric (EWOD) is a popular technology for operations on pin-constrained digital microfluidic biochips (PDMFB) [10]. The trapped charge problem is the major factor in degradation of chip reliability, and this problem is induced by excessive applied voltage. In PDMFB, signal merging is an inevitable consequence and results in trapped charges due to unawareness of the applied voltage. Apart from this, another concern is the wire routing required for accomplishing electrical connections, this increases the design complexity of pin-constrained EWOD chips [10]. However, previous research failed to address the problems of excessive applied voltage and wire routing. A network-flow-based algorithm for reliability-driven pin-constrained EWOD chips is presented in [21]. The proposed algorithm not only minimizes the reliability problem induced by signal merging, but also prevents the operational failure caused by inappropriate addressing. A work in [26] focuses on certain betterment in the generic broadcast addressing scheme. The authors have dealt with interconnect routing issues. A network flow based pin count aware routing is the major ploy. This method combines pin count minimization along with wire length minimization of interconnects. Broadcast addressing scheme optimally combines non conflicting electrodes together to address via single pin. In this process different control signals are converged together and some unwanted redundant actuation occurs. This increases power consumption, which affects product lifetime and reliability. A power aware broadcast addressing scheme is proposed in [23]. In this work minimization of pin and minimization of power, both have been taken under consideration and the basic dependency is represented by a compatibility graph. Normally pin count aware droplet routing schemes attempts to optimize number of pins after obtaining a routing schedule. In [24], authors have implemented pin reduction interleaved with stages of droplet routing. The authors applied integer linear programming method to derive droplet routing schedule in a confined routing space, finally a deterministic integer linear programming approach was applied to assign the pins in the form of decision problem.

An application-independent design method for pin-assignment configuration with a minimum number of control pins has been cited in [30]. Layouts of commercial biochips and laboratory prototypes are used as case studies to evaluate the proposed design method for determining a suitable pin-assignment configuration. In [18], authors have proposed a new technique for interconnection wire routing for the control electrodes operating at identical time sequence. They have defined a double layer dual wire system running in parallel along two separate planes in mutually perpendicular directions. Authors have further proposed an algorithm to develop a feasible wire plan for a given layout with an aim to optimize the overall number of pin count. A problem/ situation independent pin assignment methodology has been proposed in [8]. Authors have developed a droplet router specifically for cross-referencing DMFB with shared control pins.