A Novel Embryonics System with Evolutionary Ability

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Abstract: - Based on an analysis of the advantages and disadvantages of row/column elimination and cell elimination repair methods in embryonics (embryological electronics, embryonics), we developed a novel embryonics hardware structure with evolutionary ability and a corresponding self-repair method. The proposed embryonics system has a function layer, a repair layer and an evolution layer. Target circuit function is implemented through the function layer, column elimination self-repair is implemented by the repair layer, and the evolution layer can be used to initiate evolution of the circuit operating on the function layer. Importantly, the proposed self-repair method has evolution property. Depending on changes in self-repair capacity, two repair modes can be used: elimination self-repair and evolution self-repair. The faulty circuit can be repaired online in real-time through the elimination self-repair mode, and the evolution self-repair mode can fully utilize the redundancy resources through evolution of the circuit form. By combining these two modes, the embryonics system and self-repair methods presented here ensure that the circuit realized on the hardware can not only be repaired in real time, but also that utilization of embryonics and the circuit self-repair capacity are improved.

Key-Words: - embryonics, self-repair capacity, evolutionary ability, elimination repair mode, evolution repair mode

1 Introduction

The proposition of embryonics[1] provides a new direction for the study of self-repairing circuits. In the past two decades, the field of embryonics has developed rapidly, and under the guidance of embryonics a series of hardware architectures with self-repair capabilities have been proposed. These architectures include a novel FPGA structure named MUXTREE[2], which exhibits both self-repair and self-replicating properties, and a general architecture of a new electronic tissue called POEtic[3] based on the POE model[4], which has been used in a voice processing application[5]. Based on a prokaryotic cell-based bio-inspired model[6], a prokaryotic bio-inspired system[7] has been developed, and a novel bio-inspired fault tolerant cellular system, Unitronics[8, 9], and a bio-inspired fault-tolerant electronic architecture SABRE[10] have been proposed. Based on Unitronics, a universal 4*4 multiplier and an object avoidance robot controller[11] were realized. A bio-inspired adaptive reconfigurable hardware architecture, termed electronic tissue[12, 13] (eTissue) has been reported, as well as a new embryonic cellular structure appropriate to finite impulse response (FIR) filters, in which an embryonic-type FIR filter[14] with online self-repair capacity was implemented. A novel reconfigurable hardware architecture with the ability to perform in-chip self-repairing was generated, and a 4-bit serial-parallel multiplier[15] was simulated. Additionally, a three-dimensional structure of the reconfigurable array[16] and its online self-diagnosis and fault-tolerance methods have been studied.

Although a variety of bio-inspired self-repair hardware architectures have been proposed, there are fundamental differences between large scales integrated silicon-based circuits and the organisms' cells and tissues. First, cellular location in an organism is highly variable compared to the fixed position of an electronic cell. Second, removal of dead cells in the organism occurs through phagocytosis and clearance by macrophage populations, while dead electronic cells persist original position. Third, intercellular communication is complex and occurs through multiple mechanisms including direct contiguity, direct contact, and indirect contact. In contrast, intercellular contact between electronic cells occurs through the transmission line, which presents some inherent limitations. Due to differences between embryonics and biological tissues, embryonics are incapable of self-repair compared to the biological tissue at the cellular level. The form of the embryonics developed on silicon is a two-dimensional electronic cell array, and the proposed self-repair methods of various bio-inspired self-repair hardware architectures are row/column elimination and cell elimination.

In the row/column elimination method, a failure of one cell provokes the elimination of the corresponding row/column, and the function of the row/column containing the faulty cell as well as that of the subsequent rows/columns will be backward-shifted, until a spare row/column is engaged. In the cell elimination method, spare cells replace faulty cells in a two-stage process. First, faulty cells are replaced by spare cells located in the same row. When the number of faulty cells in a row exceeds the number of spare cells, row elimination occurs. Since a cell failure is expected to result in removal of the entire row/column using the row/column elimination method, the repair capability of the embryonics array cannot be maximized (i.e. cell resources are wasted). The cell elimination method is a highly efficient use of spare cells; however, the complexity of cells is increased due to the extra memory and logic required for re-routing data after reconfiguration[17].

Here we describe the development of an embryonics system with evolutionary capability and a novel corresponding self-repair method based on the embryonics system. Our proposed embryonics system contains distinct layers for function, repair, and evolution. The function and repair layers can implement the target circuit's function, repairing the circuit through the row/column elimination method when faults occur, while the evolution layer can repair the circuit by causing the circuit to evolve when it cannot be corrected by the repair layer. The corresponding self-repair method contains the evolutionary property, and the specific repair mode is chosen according to the self-repair capacity of the target circuit. If the self-repair capacity of the circuit operates at a high level, the faulty circuit can be repaired via row/column elimination without changing the form of the circuit. When the self-repair capacity of circuit is relatively low, the form of circuit evolves and the self-repair capacity of circuit is increased.

The rest of this paper is organized as follows. In Section 2, the structure of the proposed embryonics systems is presented. The features of each layer are introduced in detail. Next, in Section 3, we describe the overall process of the corresponding self-repair method with evolutionary property, and the flow of the self-repair method is introduced. Especially the evolution self-repair mode in the proposed self-repair method is studied in Section 4, and a mathematical modeling is built for evolution self-repair. The mathematical modeling is solved with genetic algorithm in Section 5, and the genetic algorithm is introduced briefly. In Section 6, we implement an experimental circuit on the proposed embryonics system, and verified its efficiency. Finally, we present conclusions and suggestions for future work in Section 7.

2 Structure of a Novel Embryonics

The structure of the designed embryonics is comprised of three layers: a function layer, a repair layer and an evolution layer (Fig.1).

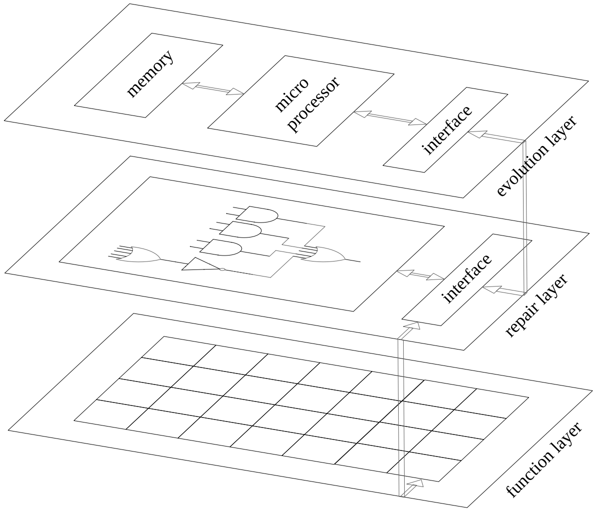


Fig.1 Layer structure of the novel embryonics

The circuit function and fault detection of the cell are accomplished by the function layer, and the detected result is sent to the repair layer, which prompts the repair layer to make a decision. The repair layer repairs the circuit operated on the function layer on-line in real-time through the row/column elimination method, based on the fault data obtained from the function layer; finally, the repair result is sent to the evolution layer. The fault data and the repair result from the function layer and repair layer, respectively, are recorded in the evolution layer; based on this information the self-repair ability of the circuit operated on the function layer is calculated. When the self-repair ability is insufficient, the circuit evolves to obtain a new target circuit form, thus adapting to the presence of faulty cells within the function layer.

2.1 Function Layer

The function layer is a two-dimensional electronic cell array consisting of basic electronic cells, each with identical structure and self-testing capability. Cell function can be configured, and target circuits of different function can be generated on the function layer under different configuration. There are two modes of intercellular connection, local connection and remote connection[18].

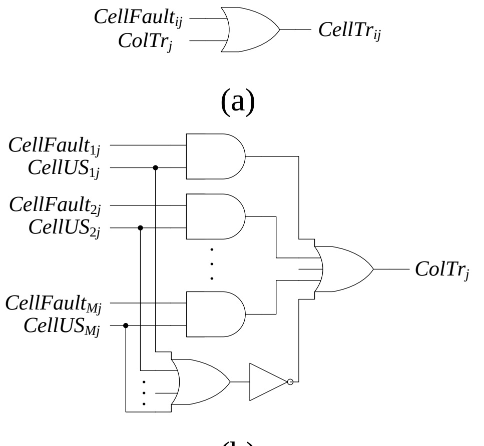
The structure of the electronic cell is designed according to the needs of the proposed structure of the electronic cell array and the self-repair mechanism. The electronic cell is composed of the Address Generator, Genes, Build-In-Test (BIT), Function Module, Switch Box and Transparent Control Module (TCM); the structures of the Address Generator, Genes and BIT have been described previously and are not discussed here.

When a fault occurs in the electronic cell, it is detected by the BIT and a cell fault signal is sent to the repair layer. After receiving the cell fault signal, the repair layer sends a transparent control signal to cells in the same column as the faulty cell. Under the control of the transparent signal, the input and output of the electronic cell are directly connected with TCM, without the process of the function module, and the faulty cell is eliminated from the electronic cell array. The transparent signal for the cell at position (*i*, *j*) can be calculated with the cell fault signal $CellFault_{ij}$ from the BIT and the column transparent control signal $ColTr_j$ from the repair layer. The $ColTr_j$ represents the column transparent control signal for the *j*th column, and is generated by the repair control circuit in the repair layer. When $ColTr_j$ =1, the entire cell in the *j*th column should be transparent. The relationship between cell transparent signal, cell fault signal and column transparent signal for a cell at position (*i*, *j*) is described by Eq.1.

$$CellTr_{ij} = CellFaulti_j + ColTr_j \qquad (1)$$

Here $CellTr_{ij}$ is the cell transparent signal, $CellFault_{ij}$ is the cell fault signal, and $ColTr_j$ is the column transparent control signal.

The circuit that generates the transparent signal for the cell at position (*i*, *j*) is shown in Fig.2(a).



(a)

(b)

Fig.2 Repair control circuit

2.2 Repair Layer

The repair layer is comprised of a repair control circuit and an interface circuit. The repair control circuit generates column transparent control signal for a defined column of the function layer. The interface circuit can transmit control signals and state signals between the repair, function, and evolution layers.

The repair control circuit input is the cell fault signal derived from the function layer, the cell using state signal from the evolution layer, and the column using state signal, while the repair control circuit output is the column transparent control signal that controls transparency of all cells in a defined column. The column using state is calculated based on the cell using state as read from memory. Based on the cell fault signals of all cells in the column and their corresponding cell using states, the repair control signals are calculated and sent to the function layer. Under the direction of the repair control signal, the state of the column in which the faulty cell is located is changed, and repair is completed. The relationships between the cell using state signal, column using state signal, cell fault signal and column transparent signal for the *j*th column are shown as Eq.2 and Eq.3.

$$ColUS_j = \sum_{i=1}^{M} CellUS_{ij} \qquad (2)$$

$$ColTr_j = \overline{ColUS_j} + \sum_{i=1}^{M} CellFault_{ij} * CellUS_{ij} \qquad (3)$$

Here $CellUS_{ij}$ indicates the cell using state signal of the cell at position (*i*, *j*), and $ColUS_j$ is the column using state signal of the jth column in the function layer. $CellFault_{ij}$ is the cell fault signal of the cell at position (i, j), and $ColTr_j$ is the column transparent control signal of the jth column.

The repair control circuit in repair layer is shown in Fig.2(b). If the ith cell in the jth column is in use and a fault occurs, the corresponding signal generated is $CellUS_{ij} = 1$ and $CellFault_{ij} = 1$, and the repair control circuit output is $ColTr_j = 1$, resulting in all cells in the jth column being transparent. If a cell is not used in the target circuit, $CellUS_{ij} = 0$, its cell fault state will not influence the state of the column in which it is located.

Data transmission between the repair, function, and evolution layers is performed using interface circuits. Through interface circuits, the cell state signal from the function layer is received, and repair control signal is sent to the function layer. The embryonics array status signal is sent to the evolution layer and configuration is received from the evolution layer.

2.3 Evolution Layer

The evolution layer is comprised of a microprocessor, a memory, and an interface circuit. The microprocessor monitors the status of the circuit operated on the function layer. When the self-repair capacity of the target circuit degenerates to a sufficiently low level, an evolution calculation is performed according to the state of embryonics array; subsequently, the resulting calculation will be configured to the function and repair layers. The configuration of the function and repair layers and the evolutionary result of the evolution layer stored in memory and evolution layer intercommunicate with the function and repair layers through an interface circuit.

3 Self-Repair Method with Evolutionary Property

In order to illustrate the proposed self-repair method, the self-repair capacity SRC of circuits operated on embryonics is defined as follows:

Definition: The self-repair capacity SRC of circuits is equivalent to the maximum number of times that circuits with self-repair property can recover from a failure state to the normal state. The self-repair capacity of a circuit on an electronic cell array using the row/column elimination self-repair method is equal to the number of redundant rows/columns in the electronic cell array.

The proposed self-repair method with evolutionary property monitors the circuits' self-repair capacity, and different self-repair strategies are used according to the extent of self-repair capacity. When the self-repair capacity of the circuit is high, the row/column elimination method of self-repair is used. In this context, a failed circuit can recover itself with the row/column in which the faulty cell is located is eliminated through row/column elimination according to the state of the faulty cell and the information obtained from the redundant row/column in the electronic cell array. The basic functional units and the connection between the units of the circuit remain unchanged during the repair process. As the number of row/column eliminations increases, the self-repair capacity of the circuit will be degenerated linearly. When the self-repair capacity reaches zero, the circuit, which only uses the row/column elimination method, is no longer capable of self-repair. In response, the circuit structure is altered through an evolving circuit form based on the functional cells remaining in electronic cell array, thus increasing the self-repair capacity of the circuit. The row/column elimination is then used for self-repair once the self-repair capacity is improved.

The entire repair process is divided into two modes depending on the difference in self-repair capacity. When the self-repair capacity operates at high efficiency, the repair process termed "elimination repair mode" is executed by the repair layer, utilizing row/column elimination. In contrast, when the self-repair capacity is operating at low efficiency, the circuit structure evolves due to the evolution layer, restoring the self-repair capacity to a high level, and the process termed "evolution repair mode". The two modes are used alternately until the evolutionary process fails and the circuit self-repair fails. The proposed self-repair process is illustrated in Fig.3.

During operation of the circuit, the cells in use are detected while the function layer executes the circuit function. When a fault is detected, a cell fault signal is propagated to the repair layer. Driven by the cell fault signal, the repair layer repairs the fault circuit using the elimination repair mode according to the redundant row/column in the embryonics array, and the repair result is transmitted to the evolution layer. The self-repair capacity (*SRC*) of circuit is calculated in the evolution layer. If the *SRC* exceeds the mode convert threshold (*Ct*), the circuit is operating normally; otherwise evolution of circuit form is initiated in the evolution layer, with the evolutionary result being stored in memory. When row/column elimination fails, a repair failure signal is transmitted from the repair layer to the evolution layer, which prompts the evolution layer to operate according to the evolutionary result. If the circuit evolves successfully, the result will be sent to the repair and function layers, and the circuit will resume normal operation. If evolution fails, the self-repair of the system fails, and the system is faulty.

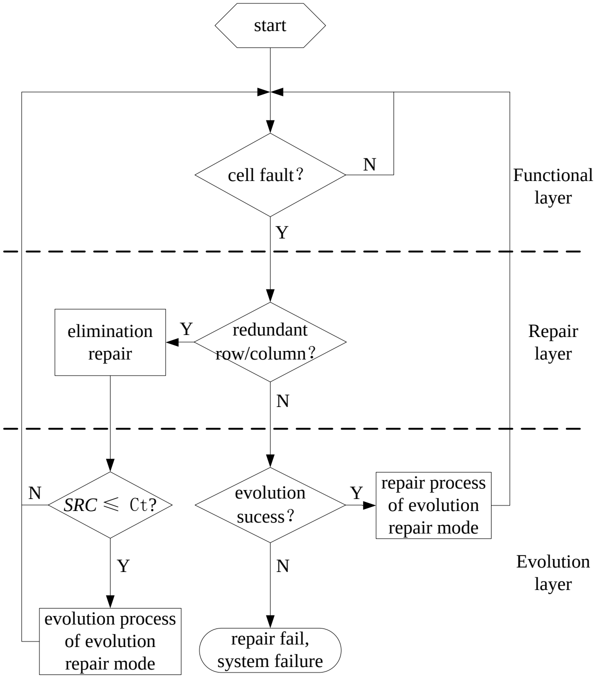


Fig.3 Self-repair process with evolutionary property

The principle of the mode convert threshold (*Ct*) setting is to provide sufficient time for the circuit evolution process. The mode convert threshold *Ct* is determined based on the empirical data of the mean time between embryonic failures and the time required by the circuit for evolution.

Throughout the self-repair process, cell detection is performed by the function layer, and the determination of redundant row/column and elimination repair is executed by the repair layer, while the calculation of the self-repair capacity and evolution repair of the circuit is implemented by the evolution layer.

4 Evolution Repair Mode

The evolution repair mode consists of evolution and repair processes. The circuit structure is calculated during the evolution process and the result is stored in the memory. During the repair process, the configuration of circuit structure from the evolution process is loaded into the function and repair layers.

The evolution process is critical to the evolution repair mode, essentially identifying circuits that meet the target function and having maximum self-repair capacity based on the electronic cell array containing faulty cells.

In order to describe the evolutionary process mathematically, variables are defined as follows:

The size of the array of the electronic cell array is $M \times N$, i.e., the function layer has M rows and N columns of electronic cells.

The electronic cell array state matrix is defined as $ES = [es_{ij}]$, where $0 \leqslant i < M$, $0 \leqslant j < N$, and es_{ij} represents the fault state of the cell at position (i, j) in the electronic cell array, $es_{ij} \in \{0, 1\}$. If $es_{ij} = 1$, the cell at the position (i, j) is normal, otherwise $es_{ij} = 0$, the cell at the position (i, j) is faulty.

The circuit coding matrix is defined as $C = [c_{ij}]$, where $0 \leqslant i < M$, $0 \leqslant j < N$, and c_{ij} is the configured chromosome for the cell located at position (i, j) and represents the function and connection of the cell. The circuits represented by different circuit coding matrixes have different functional units and connections, resulting different function and self-repair capacity *SRC*.

The cell state matrix is defined as $CS = [cs_{ij}]$, where $0 \leqslant i < M$, $0 \leqslant j < N$, and cs_{ij} represents the using state of the cell at position (i, j) in the embryonics array, and $cs_{ij} \in \{0, 1\}$. If $cs_{ij} = 1$, the cell at position (i, j) is in use, otherwise the cell at position (i, j) is idle.

$R(C, ES)$ represent the cell states calculation functions, according to the circuit coding matrix C and the embryonics array state matrix ES; the position of cells used in the circuit can be calculated and the cell state matrix CS can be obtained using this function.

The function mapping circuit coding matrix C to circuit function $Mp(\bullet)$; the $Mp(\bullet)$ function can be used to calculate the corresponding circuit function of circuit coding matrix C.

The function that the target circuit implements is denoted as F.

The evolutionary process can be described as follows: Under the embryonics array state matrix *S*, selecting a circuit coding matrix *C* to meet circuit function *F*, and maximizing the circuit's self-repair capacity *SRC*, i.e. in the solution space *U* that satisfies function *F*, finding the circuit coding matrix ***C*** corresponding to maximum (*SRC*). The evolution equation can be formulated as the following optimization equation shown in Eq.4.

$$\begin{cases} \max\limits_{C \in U}(SRC) \\ U : Mp(C * ES) = F \end{cases} \tag{4}$$

Here

$$SRC = N - sum((CS^T \times I_{M\times 1}) \,\&\, I_{N\times 1}) \tag{5}$$

$$CS = R(C, ES) \tag{6}$$

$$C * ES = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{M1} & c_{M2} & \cdots & c_{MN} \end{bmatrix} * \begin{bmatrix} es_{11} & es_{12} & \cdots & es_{1N} \\ es_{21} & es_{22} & \cdots & es_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ es_{M1} & es_{M2} & \cdots & es_{MN} \end{bmatrix}$$

$$= \begin{bmatrix} c_{11} * es_{11} & c_{12} * es_{12} & \cdots & c_{1N} * es_{1N} \\ c_{21} * es_{21} & c_{22} * es_{22} & \cdots & c_{2N} * es_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{M1} * es_{M1} & c_{M2} * es_{M2} & \cdots & c_{MN} * es_{MN} \end{bmatrix} \tag{7}$$

$$c_{ij} * es_{ij} = \begin{cases} c_{ij}, & if\ es_{ij} = 1 \\ 0\ , & if\ es_{ij} = 0 \end{cases} \tag{8}$$

According to Eq.2 and Eq.3, Eq.1 also can be written as

$$\begin{cases} \max\limits_{C \in U}(N - sum((R(C, ES)^T \times I_{M\times 1}) \,\&\, I_{N\times 1})) \\ U : Mp(C * ES) = F \end{cases} \tag{9}$$

The evolution process is achieved by solving Eq.9 and storing the calculation results. Although a variety of intelligent algorithms can be used to solve the problem, here we employ a genetic algorithm. The calculation result is the configuration of the function layer and repair layers, and is stored in memory for use during the repair process.

5 Solution of Evolution Self-Repair

In this work, the evolution self-repair property is implemented with the Genetic algorithm (GA). In order to obtain the solution of Eq.9, we developed a GA-based procedure.

5.1 Brief Introduction of GA

GA is one of several evolutionary algorithms which drew inspiration from Darwin's theory of evolution, and its characteristics are population-based evolution, survival of the fittest, directed stochastic, and a lack of dependence on gradient information. The primary operations of GA are chromosome encoding, fitness calculation, selection, crossover, and mutation. For a given problem, the potential solutions are encoded as bit strings, and a bit string which is an abstraction of a biological DNA-based chromosome can be considered as a chromosome. The populations of chromosomes are manipulated using GA, after which the quality of each chromosome in the population is evaluated using a fitness calculation. Using fitness as a discriminator of solution quality, appropriate chromosomes are selected for crossover operations. The selected chromosomes then undergo crossover to form new chromosomes which are members of a child-population. Chromosomes with higher fitness have a greater chance to generate child-chromosomes than those with lower fitness, thus creating selective pressure towards more highly fit solutions. The mutation operation randomly flips one or more allele values in a chromosome. The pseudo-code of GA is as follows.

```
a: begin
b:     Initialize population;
c:     Evaluate individuals;
d:     while stop criteria not met do
e:         Select individuals;
f:         Crossover individuals;
g:         Mutate individuals;
h:         Evalute individuals;
i:     end
j: end
```

5.2 Solution flow with GA

The solution flow with GA is indicated by Fig.4. First, the solution of the problem is encoded as an individual, and the population consisting of individuals is initialized. The solution of the evolution self-repair process is the circuit coding matrix $C = [c_{ij}]$, and is encoded to be an individual as follows:

individual: $c_{11} \cdots c_{1N}\ c_{21} \cdots c_{2N} \cdots c_{ij}\ \cdots c_{M1}\ \cdots c_{MN}$

Where c_{ij} is a bit-string representing the chromosome of the cell in position (i, j).

Every individual in the population is then mapped to the circuit, and the function of the circuit is evaluated.

The evaluation result is one component of fitness, and based on the evaluation result the *SRC* of the circuit at full function is calculated using Eq.2 and Eq.3. An individual's fitness is also defined in part by the *SRC;* if the *SRC* of a circuit meets the requirement of the optimized circuit, then the individual is the solution and the evolution process ceases.

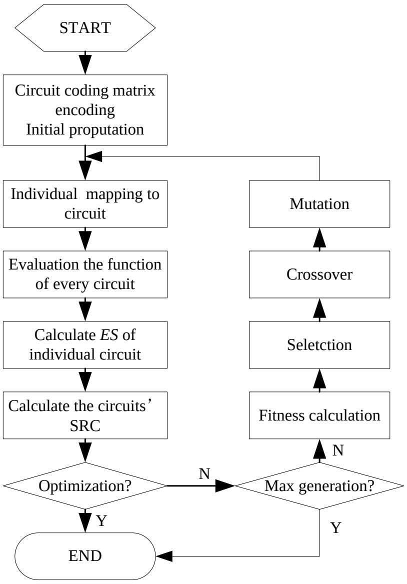


Fig.4 Solution flow with GA

Fitness provides a basis for selection, crossover and mutation, where fitness consists of both the function and the *SRC* of the circuit. Fitness can be calculated as follows:

$$fitness = \frac{SS}{AS} + \frac{SRC}{N} \tag{10}$$

where *AS* is the number of the target circuit's state, *SS* is the number of the right state of the evaluated circuit that matches the states of the target circuit, *SRC* is the self-repair capacity of the evaluated circuit, and *N* is the column number of embryonics.

SRC is calculated for a circuit with full function, while the *SRC* of a partially functional circuit is zero.

Based on the fitness obtained from the above fitness calculation, individuals in a population can be selected for crossover and mutation, thus generating a child population. The solution process is repeated until the optimal solution is generated or the maximum generation is achieved.

6 Simulation Experiment and Analysis

Based on the proposed embryonics system, an experimental circuit was implemented as an example. The circuit is composed of three D flip-flops, two inverters, and thirteen gate circuits, as well as a clock input, four signal inputs, and an output. As shown in Fig.5, *clk* is the clock input, *in*1, *in*2, *in*3, *in*4 are the signal inputs, *out* is the output of the experimental circuit, and DF is the D flip-flop. The mode convert threshold *Ct* is set to zero, and when the circuit can no longer repair itself through elimination repair, evolution repair is initiated.

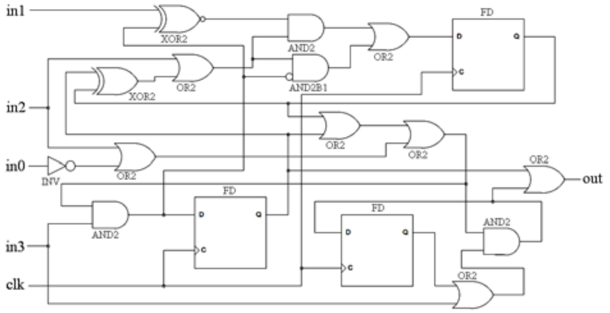


Fig.5 Experimental circuit

The experimental circuit is implemented based on the proposed embryonics system, and the size of the electronic cell array in the function layer is three rows by four columns. Through function differentiation, the circuit is implemented on the function layer with the self-repair capacity *SRC*=2 (Fig.6(a), the cells composed of Fig.6(a) is shown as Fig.6(c)). The expressed chromosomes of every cell in use are shown in Table 1.

Table 1 Expressed genes of the used electronic cells

Cell	Expressed gene
(1, 1)	1101111111111001111111111 1000100011110001 1 1010111010101110
(2, 1)	1111111110000111111111100 1110111000100000 1 1001101010011010
(3, 1)	1111111111111011000111111 1111011001000010 0 0000111100000110
(1, 2)	1111111111111110111111111 1111100101100000 0 0000101000001110
(2, 2)	1111110111111111111111111 1000111101100000 0 0000000000010000
(3, 2)	1111111100011111111111111 1110111011100100 1 0100010001000100
(1, 3)	1111111111111011111111111 0000000000000000 0 0000000000000000
(1, 4)	1111111111111011111111111 0000000000000000 0 0000000000000000

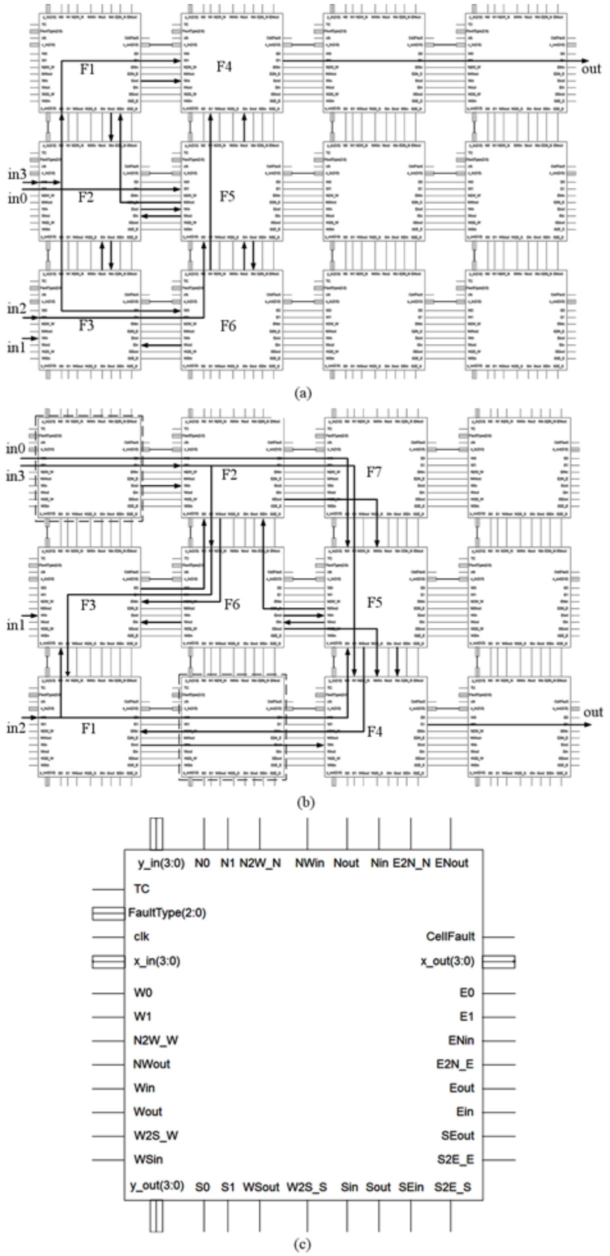


Fig.6 Realizations of the experimental circuit

The node functions F1, F2, F3, F4, F5 and F6 are as follows:

$$n23 = (\overline{in3} * F1) + n17$$

$$F1(n+1) = n23(n)$$

$$n13 = (\overline{in3} * n19) + (in3 * \overline{n17} * \overline{n19}) + (n17 * n19)$$

$$F2(n+1) = n13(n)$$

$$F3 = (in2 * \overline{in1}) + (\overline{in1} * \overline{F2} * F6) + (\overline{in1} * F2 * \overline{F6})$$

$$\overline{F4} = (\overline{in3} * \overline{F6} * F1) + (\overline{F6} * n17)$$

$$F5 = \overline{in2} * in0 * \overline{F2} * \overline{F6}$$

$$n18 = in3 * \overline{n17}$$

$$F6(n+1) = n18(n)$$

Here $F1$, $F2$, $F3$, $F4$, $F5$ and $F6$ are the outputs of nodes F1, F2, F3, F4, F5 and F6, and $F3$ also represents the experimental circuit output.

When a fault occurs in the cell located at (1, 1), the output of the repair control circuit in the repair layer $ColTr_1$ will be 1, and all electronic cells in the first column will be transparent. The function of the first and the second columns will shift to the second and third columns, respectively, and the circuit will be repaired through column elimination (Fig.7b). When a fault occurs in the electronic cell located at (3, 2), the $ColTr_2$ will be set to 1 by the repair control circuit in the repair layer, and all electronic cells in the second column will be transparent. The function of the second and third columns will shift to the third and fourth columns, respectively (Fig.7c). Since there are no redundant columns in the function layer, the circuit will not be able to repair itself through column elimination if a fault occurs, and therefore the self-repair capacity (*SRC)* is zero.

When the repair capacity deteriorates to zero, the evolution repair process is activated. If the electronic cells at (1, 1) and (3, 2) are faulty, in the evolution repair process the embryonics array state matrix is:

$$ES = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}$$

The circuit coding matrix is coded as an individual in GA, and the length of an individual is 57*3*4 = 684, with a population of 100 individuals. The evolution is computed based on the flow shown in Fig.4. In the evolutionary process the generation gap is 0.95, the probability of crossover occurring between pairs of individuals is 0.8, the mutation probability is 0.1, and the maximal generation is 2000.

Table 2 Cells' Expressed gene after evolution repair

Cell	Expressed gene
(2, 1)	111111111111111111001111 1000011000100010 0 0000111100000110
(3, 1)	111111111000111010111111 1101110111110011 1 1010111010101110
(1, 2)	111111111111011010101111 1111111100011000 1 1001101010011010
(2, 2)	101111111000111111111111 1101110111010010 1 0100010001000100
(1, 3)	111111111111111111101100 0000000000000000 0 0000000000000000
(2, 3)	111111111111111111011111 1000110001010110 0 0000000000010000
(3, 3)	111111111000111111111111 1101010101100100 0 0000101000001110
(3, 4)	111111111111011111111111 0000000000000000 0 0000000000000000

With the activation of evolution repair, another circuit with identical function can be obtained (Fig.6(b), Fig.8d, and , the cells composed of Fig.6(b) is shown as Fig.6(c)). The cells at (1, 1) and (3, 2) are faulty and transparent and the expressed chromosome of every cell in use at this point is provided in Table 2.

Through evolution repair, self-repair capacity (*SRC*) is increased to 1. When a fault occurs in the cell at position (2, 3), the circuit will be repaired through column elimination. In this scenario, the third column will be eliminated and the fourth column will implement the function of the third column (Fig.7e).

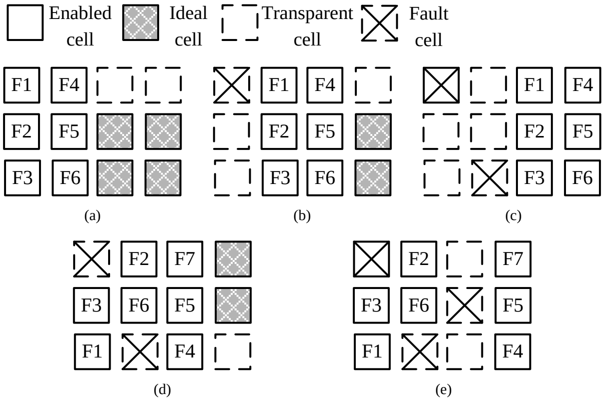


Fig.7 Self-repair process of a given circuit

From the experimental circuit repair process based on the proposed self-repair method shown in Fig.7, it is apparent that, in traditional embryonics, the circuit's self-repair capacity becomes zero in the absence of redundancy columns, causing loss of self-repair ability (Fig.7c). Using the evolution repair mode, the form of a circuit can evolve based on the embryonics with faulty cells, and the self-repair capacity of the evolved circuit improves. Both the number of the circuit's fault tolerance and the length of the circuit's life cycle is increased by the evolution repair mode.

The self-repair capacity of the circuit whose self-repair process is shown in Fig.7 is changing as Fig.8. And we can see that the self-repair capacity decreases linearly with increasing numbers of repairs using the column elimination strategy, as the points a, b, and c in Fig.8. When the self-repair capacity is zero (Fig.8, point c) the traditional self-repair method is no longer capable of repair, and subsequent circuit faults cannot be repaired. Using the proposed self-repair method with evolutionary property, subsequent circuit faults can be repaired through evolution repair mode and the self-repair capacity can be increased rapidly (Fig.8, point d). Once the self-repair capacity has improved, column elimination repair can be used.

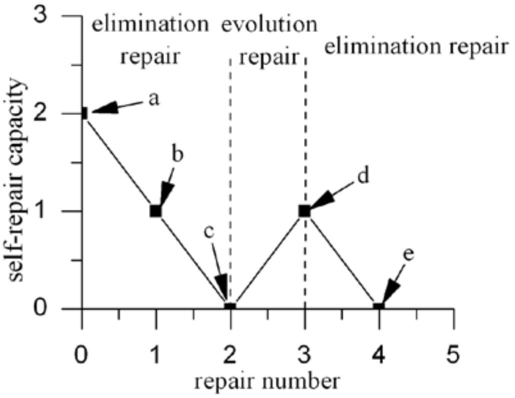


Fig.8 Self-repair capacity changing in repair process

Based on the proposed embryonics system with evolutionary property, the self-repair capacity of circuit throughout the life cycle is improved (Fig.8).

7 Conclusion and Future Work

We propose a new embryonics structure and a novel self-repair method with an evolutionary property, in which the self-repair method has been analyzed and the efficiency of the method verified through simulation experiments. We also demonstrate improved self-repair capacity of the circuit implemented on the proposed embryonics system.

The cell structure used in the simulation experiment has been used in previous studies although the requirement for large memories to store configured information is problematic. The evolution algorithm is problematic in that the evolution speed is not rapid enough for large-scale circuit structures. Future research is aimed at addressing these issues; additionally, in order to solve the problem in the simulation experiment, the electronic cell structure and the evolutionary algorithm used in the evolution repair mode will be further investigated.

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