An Evaluation of Different Fault-Tolerant Systems

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Abstract – This paper deals with study of different fault-tolerant systems and their performance evaluation. Here four types of fault-tolerant systems which includes Triple modular redundancy (TMR), Self-healing, MUXTREE, Self-repairing based on endocrine cellular communications methods were compared. And their performance evaluated in terms of Hardware overhead, simultaneous and functional fault coverage, unutilized resources and extra hardware required for rerouting.

Index Terms – Fault-tolerant systems, functional fault coverage, redundancy and endocrine cellular communications.

1. INTRODUCTION

An electronic system have become an important tool for interpretation and processing of information. But, day by day innovations in this field have made digital systems more complex than ever before. With this increased complexity the effects that affect the normal operation like noise, cross-talk and other errors also had been increased. Improper functioning of the logic circuits in the digital systems can result in deviations of the values from the designed values. Also, a single error can destroy the entire system. There for, reliable performance has become an important requirement for an electronic system. To achieve reliability for systems operating in remote areas fault-tolerant systems have proposed.

Fault tolerance is the property that enables a system to continue operating properly in the event of the failure some of its parts. Avizienis formulated the concept of fault-tolerance as "We say that a system is fault-tolerant if its programs can be properly executed despite the occurrence of logic faults" [1]. Fault tolerance now becomes a very important characteristic of modern electronic system, especially where immediate human intervention has not possible like deep sea and outer space.

In this paper, four types of fault-tolerant systems which include Triple modular redundancy, Self-healing system, MUXTREE system and Self-repairing system inspired from endocrine cellular communication were compared.

2. OVERVIEW OF DIFFERENT FAULT-TOLERANT SYSTEMS

Different Fault-tolerant system taken here are

2.1. Triple Modular Redundancy(TMR) method

Von Neumann proposed DMR technique, which had been used in early stages of fault tolerant systems [1].

2.1.1. Basic structure

In a TMR system, it consists of 3 modules of the same logic functions which ran in parallel and their output connected to a voter to produce a single output. If any one of the three systems fails, the other two systems can correct and mask the fault. Thus the faulty module could be distinguished by comparing the outputs of the same module and voting for the majority one [1].(Figure 1)

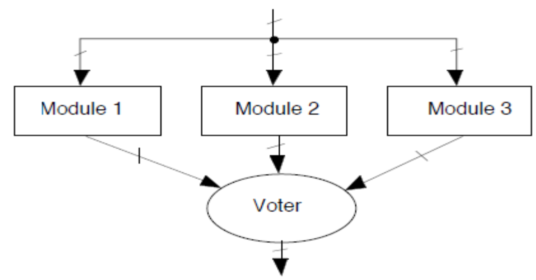

Figure 1 TMR architecture

In fault- tolerant systems by TMR method, it composed of functional block (FB) and a spare block (SB) correspond to each FB, which has same modules and routing as the functional block .If any fault is detected in the FB it is automatically switched to the SB.

2.2. Self –healing system

Self-healing describes any device or system that has the ability to perceive that it is not operating correctly and, without human intervention, make the necessary adjustments to restore it to normal operation [6]. In recent years, there has been a significant interest in using the principles of biological processes to create powerful fault-tolerant digital systems [2]-[7].

This self-healing method proposed by Lala, inspired from antigen protection mechanism employed by the human immune system i.e., any antigen is detected in the body it is automatically destroyed by the white blood cells [3].

2.2.1. Self-healing architecture

In biological systems, all cells are identical, but have different genetic code which defines its function. Inspired from this the self-healing systems were consisting of identical functional cells (F) and spare cells (S) which are used to replace faulty functional cells. As can be seen in the diagram 2.3, each functional cell is surrounded by two spare cells and two router (R) cells [6]. (Figure 2)

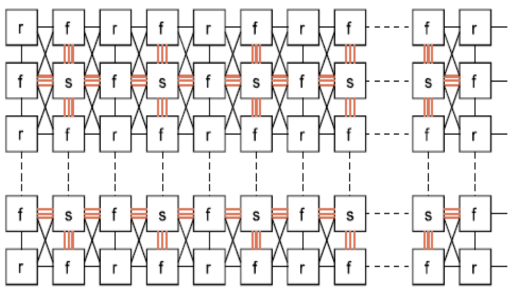

Figure 2 Self –healing architecture

When a functional cell is faulty, a suitable spare cell is selected and the inputs of the faulty functional cell are transferred as inputs to the selected spare cell. A router cell has a functional cell at its north, south, east and west, and spare cell at its NE, SE, SW and NW corners. A router can used to transfer the output of an internal cell to an external output at the periphery of the structure [6]. The architecture consists of a large number of interconnections among functional, spare cells and router cells.

2.2.2**.** Rerouting after fault recovery

Require additional hardware for the rerouting after the replacement of a cell. The self-healing approach has a router cell that helps the system bypass a faulty cell after replacement of a cell. If a functional cell (F2) is substituted by a spare cell (S1), the router cell connects the output of the functional cell (F1) to the new functional cell.

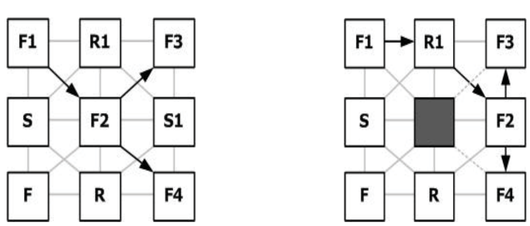

Figure 3 Rerouting in the self-healing approach.
(a) State before the fault Occurrence. (b) State after the fault occurrence F: functional cell. S: spare cell. R: router cell. S1 is replaced by F2

2.3. MUXTREE method of Self-repair

C.Ortega[2] proposed a new approach called Embryonics. Embryonic is the application of concepts of the biological cell to the design of digital circuits [2]. As the biological cells carry the genetic code of the whole system and are differentiated according to the location of the cell in the system, an embryonic self-repairing circuit is organized with building blocks that have identical structures and that vary according to the expressed genetic code in each block [2]–[5]. Tempesti proposed MUXTREE method of self-repair inspired from Embryonics [5].

2.3.1. Architecture

The Embryonics architecture is based on four hierarchical levels of organization [3].

1. The basic primitive of our system is the molecule, a multiplexer-based element of a novel programmable circuit.
2. A finite set of molecules makes up a cell, essentially a small processor with an associated memory.
3. A finite set of cells makes up an organism, an application-specific multiprocessor system.
4. The organism can itself replicate, giving rise to a population of identical organisms.

In MUXTREE method, the digital circuit is converted into an array of MUXTREE cells. Information about the initial connection is encoded as the gene in the MUXTREE cells.
The MUXTREE method comprised of different hierarchical levels: molecular, cellular, organ and population level. One component in the upper level is the aggregation of the component in the lower level (Figure 4).

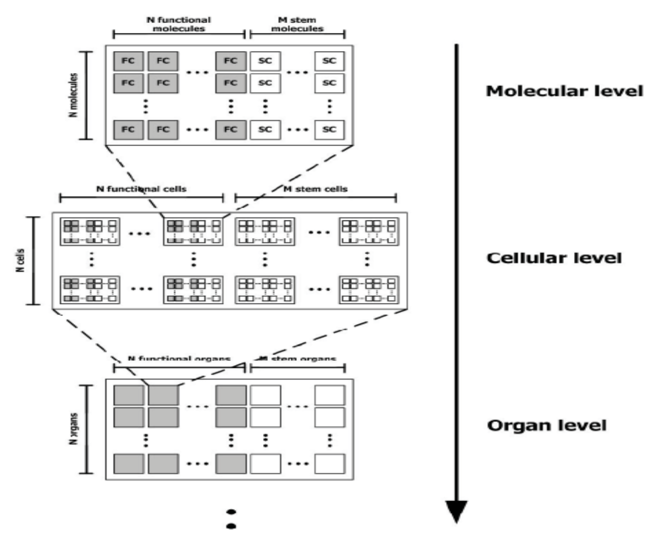

Figure 4 Hierarchical structure of a MUXTREE system

At the molecular level, it is consisting of M stem molecule for N functional molecule. The faults have detected by duplicating the module of the molecule and comparing the output. If a fault occurred in the functional block it can be replaced by the stem molecules until all the stem molecules has replaced by the functional molecule. If there is additional stem cell to replace for further faults then the whole cell have to be replaced. An extra hardware dynamic routing has used of rerouting the cell after fault recovery. The MUXTREE approach has additional MUXs and DEMUXs for the rerouting process after the replacement of a cell. Each cell has them that can bypass vertical and horizontal signals by changing the selection bits of the MUXs and DEMUXs. MUXTREE system can be recovered from functional fault as many times as the number of columns of SC.

2.4. Self-repairing digital system with unified recovery process

A.J. Greensted (2005) has observed that self-repairing digital system inspired from endocrine cellular communication can be used as an alternative for fault-tolerant systems [7]. In endocrine cellular communication, endocrine cell secretes a specific hormone for cell replacement only after it receives another specific hormone of damage cell indication. By adopting the similar mechanism, proposed system isolates the faulty cells and replaces with a proper spare cell [8].

2.4.1. Architecture overview

The architecture of self–repairing digital system composed of two layers: Functional layer and Gene control layer (figure .5) which are operated in parallel.

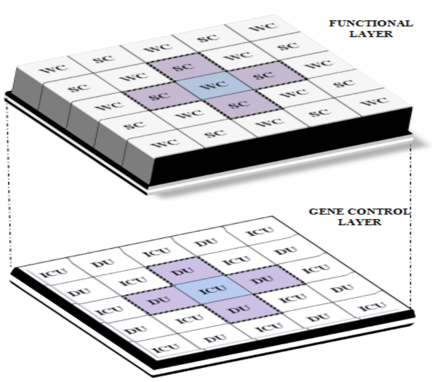

Figure 5 Architecture overview

2.4.2. Functional layer:

Functional layer consist of working cells (WC) and stem cells (SC). The structure of each cell is identical the only difference is the genome which contains the information about function and connection. Each working cell is surrounded by four stem cells which composed of same modules and input output connection as the WC. Therefore, WC can be replaced by any one of the four SC after fault occurred by properly assigning the same genome to the stem cell, while wiring architecture connects the stem cell correctly [8].

Functional layer also composed of the Fault detection unit**.** Here, the fault detection has done by using duplicates of the same module and comparing the outputs of the each module with the output of the other module. If the outputs are not same then fault signal is generated.

2.4.3**.** Gene control layer

Gene control layer replaces the faulty WC with SC without any collision. It finds available spare cell and selects proper genome to the particular spare cell. Then the spare cell takes the functionality of the faulty working cell.

3. PERFORMANCE EVALUATION PARAMETERS

3.1 Hardware Overhead

In fault-tolerant system the hardware additional to that of the functional modules regarded as its overhead. Thus, here the hardware for rerouting and spare cells is considered as overhead. Hardware overhead is calculated as,

$$(1)\quad Overhead(\%) = \frac{No.og\ spare\ cells + No.of\ hardware\ for\ rerouting}{No.of\ working\ cells} \times 100$$

3.2. Simultaneous fault coverage

Simultaneous fault coverage is the number of faults that can be recovered in the system at the same time.

3.3. Functional fault coverage (FFC)

Functional fault coverage is the maximum number of fault that can be tolerated for a single functional cell in the system.

3.4. Unutilized resources

Unutilized resources are the maximum number of unutilized cells for fault recovery even though the cell is not faulty.

3.5. Additional Hardware for rerouting

It is the hardware required for rerouting among basic modules after fault recovery.

4. RESULTS AND DISCUSSIONS

The four above fault-tolerant systems are compared based on N×N array of functional cells. Table 1 and Table 2 summarizes the comparison with other approaches

In TMR method, each functional cells consist of two redundancies and thus the overhead is 200% and in the case of self-healing system, the number of router cells and spare cells are half that of functional modules, therefore the overhead is 100%. In MUXTREE and self-repairing system the overhead is calculated by (1).

Since, MUXTREE system does not refer to any simultaneous faults, its simultaneous fault coverage is one. But in the case of other systems it can be recovered from simultaneous faults until the number of faults does not exceed the number of spare cells. The number of spare cells in the case of TMR and self-healing method is one therefore their functional fault coverage is also one. In MUXTREE system it can be recovered as many times as the number of columns of SC and that in self-repairing system the FFC can be four.

Approach	Number of WC	Overhead (%)	FFC
TMR	N×N	200%	1
Self-healing system	N×N	100%	1
MUXTREE system	N×N	$100 \times (1 + {}^{2M}/_{N})\%$	M
Self-repairing system	N×N	$100 \times (1 + {}^{2}/_{N} + {}^{1}/_{N})2\%$	4

Table 1 Comparison of Hardware overhead an FFC

One of the two redundancies is useless after a fault occurs in the functional cell and one redundancy is being used therefore the unutilized resources is equal to number of functional cells in TMR method. There are no unutilized resources for self-healing and self-repairing systems. In MUXTREE systems the unutilized resources increases as the system becomes larger.

Approach	Number of SCs	Simultaneous fault coverage	Number of hardware for rerouting
TMR	2×N×N	N×N	-
Self-healing system	(N×N)/2	(N×N)/2	(N×N)/2
MUXTREE system	N×M	1	N(N+M)
Self-repairing system	(N×1)(N×1)	N×N	-

Table 2 Comparison Simultaneous fault coverage and Number of hardware for rerouting

The main disadvantage of Self-repairing and MUXTREE methods is that; they require additional hardware for rerouting after the replacement of a cell. The self-healing approach has a router cell that helps the system to bypass the faulty cell after the replacement of the cell. The MUXTREE approach has additional MUXS and DEMUXs for the rerouting process .Each cell has MUXs and DEMUXs which bypass the vertical and horizontal signals by changing the selection bits. But the Self-repairing system does not require such additional hardware for the rerouting process after the cell replacement, because the replacement of the cell also accompanies the necessary rerouting.

5. CONCLUSION

Different fault-tolerant systems and their comparison are presented in this paper. Among them the TMR and self-repairing methods become worse in the case of FFC and hardware overhead. As the system become larger, the self-repairing system out performs or at least as the same level as the other system in terms of hardware overhead and only worse than the MUXTREE system in terms of FFC. But in MUXTREE system unutilized a large number of modules as the system becomes larger.

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