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DIVERSIFICATION TECHNIQUES OF FAULT-TOLERANT SYSTEMS ON FPGAS USING CAD-BASED AND GENETIC ALGORITHMS-BASED DESIGNS

In this paper we analyze several techniques to diversify fault-tolerant FPGA-based systems. Also we suggest diversification technique based on the genetic algorithms, which have the wide application in testing and other areas. This technique has been illustrated by the example of heating controller model for AN-70 plane.

PLD-based systems, fault-tolerance, defects, diversification, genetic algorithms

Introduction

The analysis of modern tendencies in control systems design shows that utilization of programmable logic devices (PLD) and, in particular, FPGA-technologies is significantly growing. On the other hand, field experience of digital control systems shows that they are critical to the faults caused by design and physical defects. Therefore developers need the special methods to provide a high level of fault-tolerance for such systems. These methods should be applied during various stages of digital control systems life cycle. The reasonable solution is to use redundancy and, particularly, version redundancy during designing fault-tolerant critical systems on FPGA-based devices since many projects for nuclear, aircraft and some other industries demand to use diversity as a standard requirement.

The analysis of existing works shows that application of diversification approach is the wide practice while building the fault-tolerant redundant systems by the standard CAD tools and there are elaborated techniques to design such systems [1]. Nevertheless the main task in case of using diversification approach is to get the most alternate versions of the same project. Practically it seems that the most effective way is exploiting different approaches to multi-version fault-tolerant systems design [1 – 4] as this significantly increases the cardinality of set, which includes variations of least correlated versions. First approach is based on computer-aided design (CAD) tools, which have the commercial orientation [2]. The second one intends to use logic of genetic algorithms (GA) [2, 5, 6]. GA-guided approach allows getting new and sometimes non-conventional configurations while implementing digital system.

The purpose of this article is to analyze existed diversification techniques of fault-tolerant PLD and to propose new technique based on mathematical apparatus of genetic algorithms (GA).

1. CAD- and GA-guided diversification of FPGA-based projects

Nowadays there are several methods to diversify FPGA-based projects. The first one is the most popular among the developers. Its exploiting is closely related with life cycle stages of system design by means of standard CAD tools [1]. This method can be utilized either during all CAD-guided design flow or during only one or several design stages. Obtaining alternative versions is possible at the following stages: choosing FPGA vendor, FPGA chip and CAD tools; design entry; compilation; testing and project verification. As a result the required number of project's versions is finally selected from the total set of initially created ones by criterion "reliability-cost".

Such approach considerably simplifies design flow as it implies the use of standard CAD tools. Unfortunately it also imposes a number of restrictions. These restrictions are connected with the fact that the automated CAD-guided design process assumes applying standard algorithms, which should be implemented by CAD tools and allow to obtain the standard set of correlated versions of the project. Therefore utilization of the CAD-guided diversification technique allows reducing the occurrence of absolute defects (for example, due to use of several CAD-systems vendors, etc.). However, in case of complex multi-version systems reduction of absolute design defects is practically insoluble issue. The occurrence of these defects is connected to the features of CAD-guided design process and also standard CAD's algorithms (practically all of them are closed that excludes an opportunity of changing a code and a synthesis technique). Additionally the quantity of relative defects, brought directly by project developers, and group defects, which appear simultaneously in several versions, rises together with increasing the number of project's versions.

The second diversification of FPGA-based projects allows to involve new and non-conventional approaches to system design that can obtain not trivial solutions of system implementation [2, 3, 4]. This method is based on applications of GA [6], which are actively developing last decade. Such GA-guided diversification method of FPGA-based projects can be applied at various levels of system design [2].

GA operates with a set of project's versions (individuals) represented as binary sequences, which encode

different variants of system implementation. GA generates new individuals using such genetic operators as selection, crossover, mutation, and inversion. If GA completes its work the required number of project's versions is selected from the final population according to their fitness factor. The design formula to calculate fitness depends on task specificity.

FPGA-based projects can be diversified at the stages of GA presetting, selection, crossing, mutation and inversion of individuals (fig. 1). GA presetting means choosing the distribution law that forms the individuals of an initial population, probabilities of applying genetic operators, complexity of GA. Also it is possible to define the selection method: roulette wheel, rank, tournament, steady-state or elite selection. At the crossing phase new versions can be generated by choosing the crossover type (single point, two point, uniform, etc.) and/or its fashion (haploid or diploid). Reception of additional versions at the next stage is possible by using either single point or uniform mutation and inversion of individuals.

The use of the GA-guided diversification method of FPGA-based projects allows reducing the occurrence of absolute design defects and lowering a number of relative and group defects as a role of the developer is replaced by GA-technique. Low level of absolute defects is the result of low correlation of the selected project's versions that is achieved due to:

– using evolutionary approaches to system's design where GA can supplement and replace standard CAD (i.e. to be some kind of their alternative);

– GA features which involve analogues of genetic inheritance mechanism and natural selection, and also application of random numbers generators (for example, while forming an initial population or application of genetic operators).

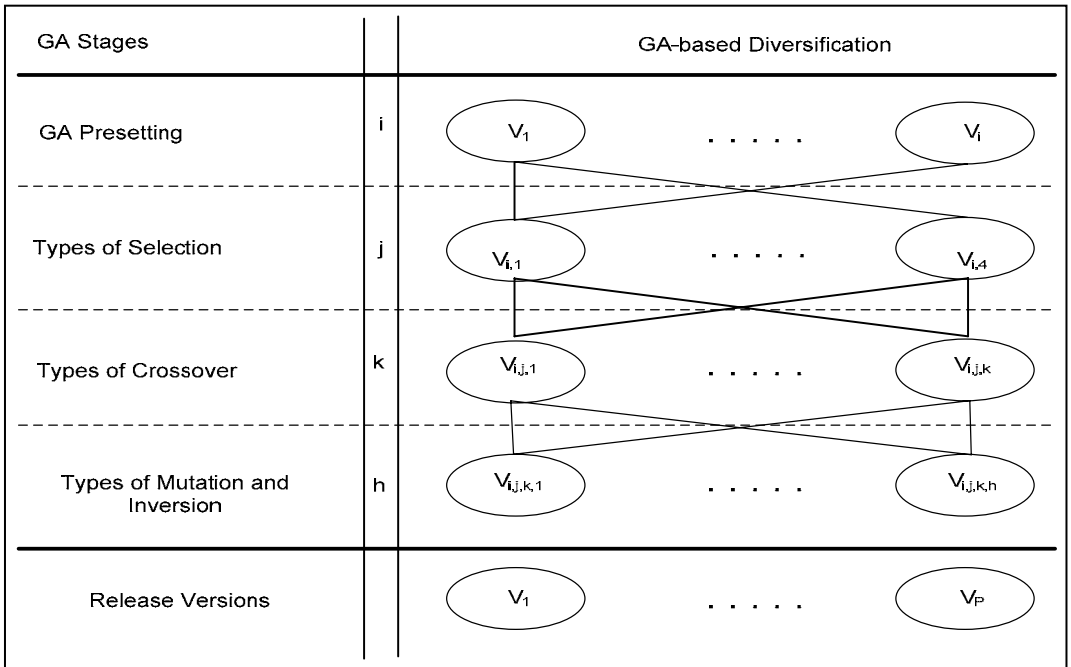

Fig. 1. GA stages where alternative versions can be obtained during GA-guided designing

Disadvantage of the GA-based design is the fact that we do not know beforehand the exact number of project's versions obtained by GA. It is caused by work features of evolutionary methods.

Thus in this context we can say about so-called external and internal diversification applying both diversification methods.

The internal diversification assumes to obtain alternative versions by only one considered above method, whereas the external one combines application of both CAD-and GA-guided techniques (fig. 2).

The carried out analysis allows to generate the following hypothesis: we need to apply the external project diversification to obtain a set of versions that have the minimal correlation among themselves as in this case we use different approaches to system design.

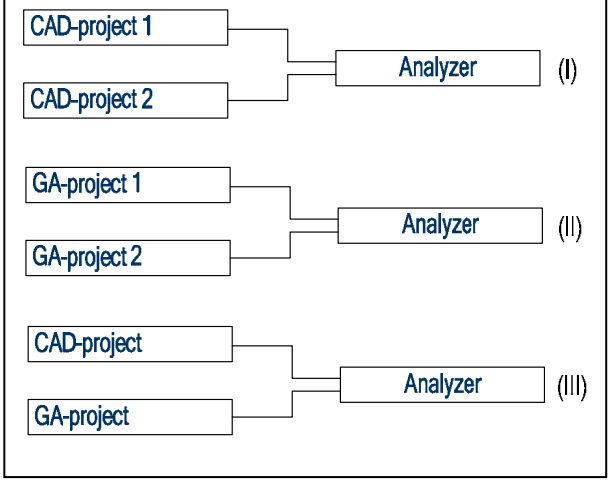

Fig. 2. Internal (I, II) and external (III) FPGA-guided diversification

2. Experience

The proposed design technique has been illustrated by series of experiments to get a model of heating controller for AN-70 plane by means of GA. After that we have carried out the comparative analysis with the existing analogue developed using standard CAD.

The simulation has been prepared at a level of implementing the project in a chip. The GA application process practically combines two stages of project's life cycle: design and realization. FPGA is represented as a homogeneous field of cells, which can be configured by submission of binary sequence on the multiplexer's inputs. They manage interconnections of cells and their internal functions. In the given model each cell has one output and four inputs which can be connected either to one of a microcircuit's inputs or an output of any cells (fig. 3).

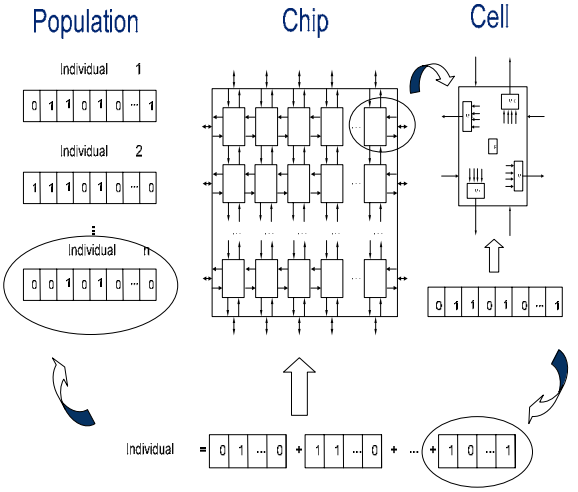

Fig. 3. GA applications at a level of realization of the project in a chip

The genotype of an initial population is formed by random numbers generator and represents a set of binary strings coding various variants of project realization. Each string consists of several genes. Number of genes is equal to the total number of cells. The following information is coded in a gene: probabilities to connect each cell's input with one of microcircuit's inputs; numbers of input pins which can be potentially connected with the cell's inputs; numbers of cells which outputs are connected to the current cell; the internal function realized by a cell; the probability that a cell is connected to one of output pins. The fitness coefficient is calculated for each individual by comparing output signals of a microcircuit with existing project specifications (the truth table of the project). Individual's fitness is defined as the ratio between correct minterms of this individual and the total number of minterms from truth table. The probability of individual's participation in further selection Ps(i) is also obtained. Then according to the value of Ps(i) new population is formed by crossover, mutation and inversion operators. GA completes its work if the maximal conformity to project specification has been achieved or the predefined maximum number of iterations has been reached. Finally the best versions with the maximal fitness are selected from the total set of project's versions in last population (fig. 4).

Table 1 shows initial data accepted for simulation.

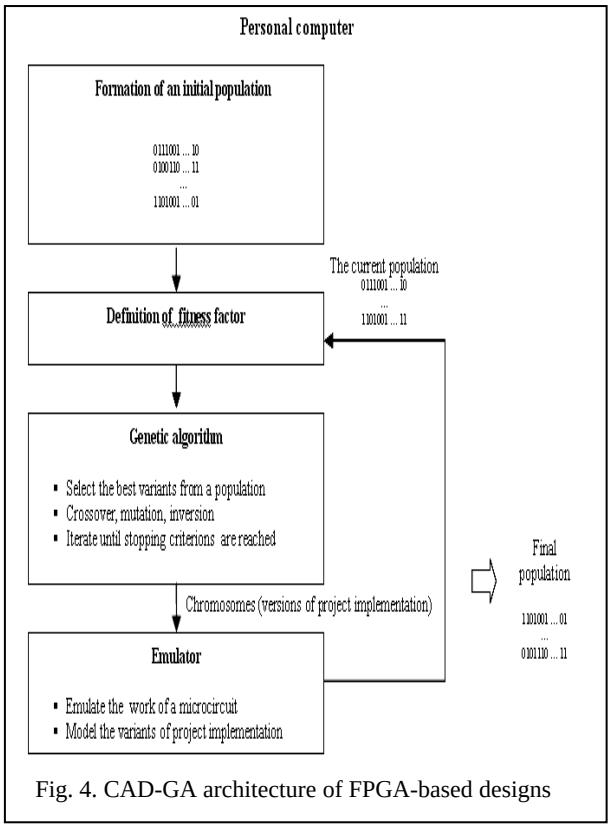

Fig. 4. CAD-GA architecture of FPGA-based designs

Table 1

Initial Data

The initial data	Value
The information on a microcircuit (the area of a field of modelling)	4×4
Requirements to the project, the table of the validity	The entrance 7-bit data: 1-st bit determines a sign, 2-7 bits determine value of temperature (°C). The output 2-bit data: '01' – the temperature is lower than 15°C, '10' – temperature from 15°C up to 35 °C, '11' – the temperature is higher than 35°C.
GA parameters options	
population size	70
type of selection	"roulette"
crossover probability	0,70
mutation probability	0,20
inversion probability	0,10
type of crossover	Uniform

As the diversity metrics we have chosen the difference of graphs topologies characterizing the interconnections of logic cells in FPGA.

The model of a heating controller has been received as the communication graph that illustrates interconnections of logic cells. The final project represents voting scheme "3 out of 5" (fig. 4).

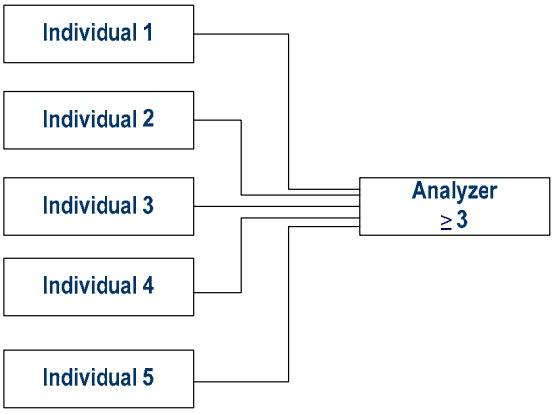

Fig. 4. The model of heating controller submitted as a voting scheme '3 out of 5'

Every minterm is correct for at least three versions as shown in fig. 5.

Comparing the given project with the existing analogue developed using standard CAD software we should note compactness of the first one as the total number of logic cells involved in GA-based design equals 68 whereas the CAD-based project involves 373 cells. So we can conclude that the GA-based method is focused on utilization of the maximal number of inputs and outputs along with minimal quantity of logic cells.

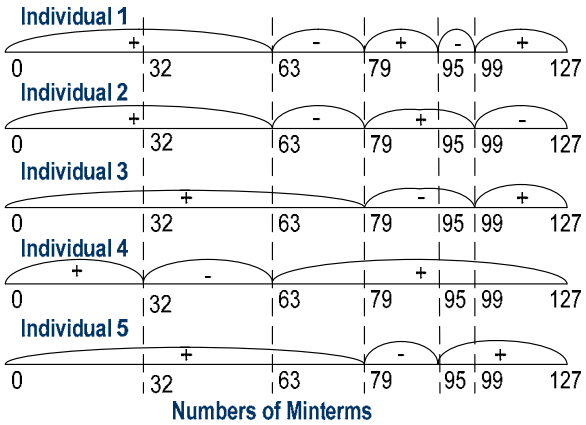

Fig. 5. The scheme of minterms overlapping in the model of heating controller submitted as voting structure '3 out of 5'

Conclusions

Nowadays using diversity is a standard requirement for many projects designed for nuclear, aircraft industries. However such approach intends to obtain the most alternate versions of the same project. The most effective way is application of different approaches to multi-version fault-tolerant systems design – CAD- and GA-guided ones.

Utilization of several diversification techniques during designing fault-tolerant FPGA-based systems allows reducing amount of design defects in such systems. The analysis of the CAD-guided diversification method shows that it can reduce a number of absolute design defects. However this method cannot reduce the absolute defects which occurrence is connected with features of design process and standard CAD algorithms. Also the number of group defects can grow if the number of project's versions is increasing.

GA-guided diversification technique allows reducing the occurrence of absolute design defects due to low correlation of the selected versions of the project. It is also avoids relative and group defects.

The performed experiment has confirmed the hypothesis that obtaining the project's versions with the least correlation among themselves is possible by application of external diversification as in this case the different approaches to system design are used. As a result of experiment GA has evolved the model of a heating controller for AN-70 plane. The comparative analysis of two models of heating controller that have been designed by CAD- and GA-based tools shows that the GA-based method is focused on using the maximal number of inputs and outputs at the minimal quantity of logic cells.

The main direction for future researches could be to work out a technique and a circuit to adaptive testing individuals (calculating their fitness) during the GA-guided design as in case of complex FPGA-based projects increasing the number of their truth table dimensions leads to growing time expenses for their testing.

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