ALGEBRAIC ANALYSIS OF FEEDBACK LOOP DEPENDENCIES IN ORDER OF IMPROVING RTL DIGITAL CIRCUIT TESTABILITY

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Abstract. *The existence of loops in a circuit structure causes problems in both test generation and application. When nested loops occur in the circuit, it is necessary to break the most nested one(s) to improve circuit testability significantly, with minimal design cost. This paper deals with a new method of breaking all loops in the register-transfer level (RTL) digital circuit structure.*

1 Related Work

It is well-known fact the occurrence of nested feedback loops in the *CUA* (*circuit under analysis*) structure causes problems in both test generation and application. The problem can be solved e.g., by breaking feedback loops by using a *DFT* (*design for testability*) structure – e.g., a scan register. There is a number of cycle searching algorithms, e.g., [11] in the literature, including several of them that can find all the cycles in polynomial average time per cycle. Also, there are many papers dealing with the "loop breaking" problem (the most known solved are: (*M*)*FVS* – (*minimum*) *feedback vertex set problem* [8] and (*M*)*FAS* – (*minimum*) *feedback arc problem* [7]) of identifying such a set of vertices (edges) of a (un)directed graph that after removing them from the graph, the graph become acyclic, i.e., all feedback loops will be broken. In VLSI testing community, there has been intensive research of (M)FVS problem due to the applications, e.g., [1, 4, 5, 2]. Generally, there are two types of algorithms: 1) exact (e.g., [8]) and 2) approximating (e.g., [3]). Exact algorithms are usually based on so-called *contractions* (see [6]), approximating ones (solution with a certain quality guaranteed) on some heuristic rules.

2 Proposed Method

A digraph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ representing the structure of all *I paths* existing within CUA was introduced in [9]. In [10], the algebraic way of computing matrix $\boldsymbol{B}_{\mathrm{f}}$ (fundamental system of cycles within $\boldsymbol{G}$) incident to a spanning tree within $\boldsymbol{G}$ was presented. Making linear combinations of $\boldsymbol{B}_{\mathrm{f}}$ rows, all CUA circles (i.e., feedback loops), together with matrix $\boldsymbol{B}$ (of all $\boldsymbol{G}$ cycles) can be constructed. In the next, consequent research results (of a new method for loop dependency analysis and for solving MFVS/MFAS) are presented briefly.

The proposed method procedure consist of these sequent steps: 1) <u>elimination of nodes</u> and edges to $\boldsymbol{G}$ contain only circles – in $O(|\boldsymbol{E}|+|\boldsymbol{V}|)$ time, 2) <u>finding a spanning tree</u> of $\boldsymbol{G}$ –

Kruskal's algorithm in $O(|\boldsymbol{E}|.\log|\boldsymbol{E}|)$ time, 3) $\boldsymbol{B}_{\mathrm{f}}$ computation: matrix transposition, matrix multiplication and Gaussian elimination for matrix inversion – in $O(|\boldsymbol{V}|^3)$ time, 4) $\boldsymbol{B}$ computation: linear combinations of $\boldsymbol{B}_{\mathrm{f}}$ rows – in $O(2^{\mu(\boldsymbol{G})})$ time, 5) determining loop dependences – in $O(\mu(\boldsymbol{G})^2)$ time, 6) finding MFVS/MFAS – in $O(\mu(\boldsymbol{G}))$ time, where $\mu(\boldsymbol{G}) = |\boldsymbol{E}|-|\boldsymbol{V}|+p$ is a *cyclomatic number* of $\boldsymbol{G}$ and p is the number of components in $\boldsymbol{G}$; in our method case, $p = 1$. In total, proposed method works in $O(|\boldsymbol{V}|^3+|\boldsymbol{E}|.\log|\boldsymbol{E}|+2^{\mu(\boldsymbol{G})})$ time.

For digraphs fulfilling condition $|\boldsymbol{E}|-|\boldsymbol{V}|+1 \leq \log_2(|\boldsymbol{V}|^3+|\boldsymbol{E}|.\log|\boldsymbol{E}|)$, our method works in $O(|\boldsymbol{V}|^3+|\boldsymbol{E}|.\log|\boldsymbol{E}|)$ time. Otherwise, the time complexity of the step 4 exceeds time complexities of the other steps and the method works in $O(2^{\mu(\boldsymbol{G})})$ time.

3 Conclusion and Acknowledgements

Relatively few exact algorithms for the MFVS/MFAS problem have been proposed. Some of them are applicable to undirected graphs, the others to digraphs, some work on general graphs, the others on special graphs. In the paper, basis of a new exact method solving MFVS/MFAS problem (for digraph class presented in [9]) was introduced. The time complexity of our method is similar to the time complexity of the other exact general-digraph methods ($O(|\boldsymbol{V}|^2.(|\boldsymbol{V}|+|\boldsymbol{E}|))$, but only for digraphs fulfilling $|\boldsymbol{E}|-|\boldsymbol{V}|+1 \leq \log_2(|\boldsymbol{V}|^3+|\boldsymbol{E}|.\log|\boldsymbol{E}|)$. Then our method works in $O(|\boldsymbol{V}|^3+|\boldsymbol{E}|.\log|\boldsymbol{E}|)$ time. Practically it means our method isn't suitable for digraphs that violate the condition. It wasn't proved our method can also work with general digraphs nor it is limited only to a certain class of digraphs.

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