circuit can be estimated from the block partition. In Fig. 4*b*, it can be seen that the next state variable *Y*3 depends on the current state variables *y*1 and *y*2, and that the two memory element pairs of (*FF*3, *FF*2) and (*FF*3, *FF*1) do not include any feedback loop between flip-flops within each pair. By assigning state codes by means of block partitioning, not only can a great reduction in area be achieved, but the difficult test generation problem for sequential circuits can be drastically simplified. In this Letter, we adopt a generalised *m*-block partitioning method for assigning the state codes and develop an efficient heuristic to minimise the dependency among the state variables. Whereas a 2-block partition is only able to consider dependencies among single state variables, our approach takes into account the dependencies among a set of state variables with *m*-block partition, thus the complex feedback cycles are greatly simplified. Thus, by considering the *m*-block partition, we are able to identify the dependencies among the set of state variables more globally, and thereby find an optimal state assignment for partial scan. In [2], non-controllability of flip-flops is evaluated by a systematic analysis of the state transitions and the encoding of the underlying FSM. In contrast to the method in [2], which is for selecting an optimal set of flip-flops for partial scan at gate level, our method considers *m*-block partition to determine optimal state encoding, which could restrict the number of non-controllable flip-flops to a minimum during the state assignment process.

The state assignment algorithm proposed in this Letter for estimating the minimum number of mutual dependencies among memory elements is summarised in Fig. 5.

Table 1: Fault coverage of different state assignments (%)

Circuit	Ns/Nb	Jedi	Random	Mm pairs	2-block	One-hot
Mark1	16/4	98.10	94.47	98.85	98.85	97.12
Bbsse	16/4	98.24	90.66	98.85	98.12	97.80
s832	25/5	97.56	98.88	97.92	45.61	86.43
Keyb	19/5	91.50	95.04	96.88	93.66	97.62
Tbk	32/5	96.97	98.59	98.98	98.98	97.38
s1494	48/6	96.81	96.34	98.26	94.87	56.97

Experimental results: For the experiments, the synthesis tool SIS from U.C. Berkeley, the partial scan design tool PSCAN from Hanyang University, and the automatic test pattern generating tool HITEC from U.C. Illinois were used. The stuck-at fault coverages for the sequential circuits synthesised by applying each state assignment and our method are compared in Table 1. The *Mm* pairs in particular gave higher fault coverage than any other algorithm for the tbk benchmark. For the keyb circuit, although our method results in 0.74% lower coverage than that of the one-hot method, it exhibits improvements of 5.78 and 1.84% over the Jedi and random methods, respectively. As expected, the *m*-block partition gives better fault coverage than the 2-block partition, and in general *m*-block performs best. The area overhead incurred by *Mm* pairs is less than or similar to that of the Jedi method, and the delay is less than that of the Jedi method but not as good as that of the one-hot method, as expected.

Conclusions: An *m*-block partitioning technique for state assignment has been proposed for minimal partial scan design. Dependencies among state variables are drastically reduced by taking closed partition and zero product pairs. Partial scan design, which is known to be highly affected by the complexity of feedback cycles, requires a lesser number of flip-flops when *m*-block partitioning techniques are used. Since all circuits are not completely *m*-block partitioned, other heuristics need to be investigated to augment the 2-block partitions.

Acknowledgment: This work was supported by Brain Korea 21 and Samsung Electronics.

31 May 2000
Electronics Letters Online No: 20001086
DOI: 10.1049/el:20001086

S. Park and S. Cho (*Department of Computer Science and Engineering, Hanyang University, Ansan Kyunggi-Do, 425-791, Korea*)

E-mail: parksj@mslab.hanyang.ac.kr

S. Yang (*Department of Computer Engineering, Pusan University, JangjunDong, kumjungGu, Pusan, 609-735, Korea*)

References

1 CHENG, K.T., and AGRAWAL, V.D.: 'A partial scan method for sequential circuits with feedback', *IEEE Trans. Comput.*, 1990, **39**, (4), pp. 544–548
2 KALLA, P., and CIESIELSKI, M.J.: 'A comprehensive approach to the partial scan problem using implicit state enumeration'. Proc. Int. Test Conf., 1998, pp. 651–657
3 CHENG, K.T., and AGRAWAL, V.D.: 'Design of sequential machines for efficient test generation'. Proc. ICCAD, 1989, pp. 358–361
4 SHARMA, S., and HSIAO, M.S.: 'Partial scan using multi-hop state reachability analysis'. Proc. IEEE VLSI Test Symp., 1999, pp. 121–126

Study of efficient FEM-based iteration method for open region problem and its application to scattering from a three-dimensional cavity-backed aperture

Jongkuk Park, Heeduck Chae and Sangwook Nam

An efficient iterative finite element method for solving a three-dimensional scattering problem is proposed. With only a small number of meshes around a three-dimensional scatterer, the typical finite element method is shown to give an exact solution by carrying out several iterative updates of the radiation-type boundary conditions. The proposed method is used to analyse the scattering from a three-dimensional cavity-backed aperture, and the results obtained show good agreement with data obtained using another method.

Introduction: A number of techniques have been proposed that involve the application of the finite element method (FEM) to radiation or scattering problems. Among these methods, hybrid methods such as the finite element boundary integral method (FEBIM) and methods incorporating various types of ABC have been widely used [1]. These methods are robust and have proved successful. However, each method has its inherent shortcomings, and many efforts have been made to improve their efficiency.

The FEM-based iteration method (or iterative FEM) has been proposed to solve electrostatic and TM 2D scattering problems in open space [2, 3], and applied to solve the 3D vector wave equation for the analysis of discontinuities in a rectangular waveguide [4].

The FEM has been shown to give an exact result effectively with only a small number of meshes near a scatterer. This method is based on the assumption that all the boundary fields are initially of the Dirichlet type. Once all the field components are solved with this given Dirichlet boundary condition, the equivalent electric or magnetic current source on the surface of a scatterer can be calculated using the equivalence theorem. From this calculated equivalent source, the scattered fields on the boundary can be computed using the appropriate Green function, and the Dirichlet boundary condition is updated using these new scattered fields. By iterating this procedure several times, a converged exact solution can be obtained.

However, this method is found to be unsuitable for characterising scattering caused by an object of a resonant size or larger due to internal resonance-like phenomena. Therefore, in this Letter, to eliminate these phenomena, a radiation-type boundary condition is proposed and incorporated into the above iterative FEM instead of the Dirichlet boundary condition.

Theory: As an example of the proposed method, the scattering from a three-dimensional rectangular cavity recessed in a ground plane is analysed. A triangular prism element [5] is used as the three-dimensional vector basis. Fig. 1 shows the structure to be analysed and a fictitious surface on which the boundary fields will be updated. Note that the boundary surface A_2 in Fig. 1 can be placed very close to the aperture surface A_1. As mentioned above, the radiation-type boundary condition should be applied to A_2 in order to avoid interior resonance-like phenomena. In general, the Sommerfeld radiation condition is satisfied in the far-field region as follows.

$$\hat{n} \times \nabla \times \mathbf{E} + jk_0\hat{n} \times \hat{n} \times \mathbf{E} = 0 \quad (1)$$

Since the boundary surface A_2, where the mesh is terminated, is placed near to the scatterer, the Sommerfeld radiation condition is not valid and must be reconstructed as

$$\hat{n} \times \nabla \times \mathbf{E} + jk_0\hat{n} \times \hat{n} \times \mathbf{E} = \mathbf{U} \quad (2)$$

This mixed boundary condition means that the left side of the Sommerfeld radiation condition does not vanish in the near-field region. The key idea in this Letter is based on updating this residual term. With this mixed boundary condition, the functional is given as follows.

$$F(\mathbf{E}) = \frac{1}{2}\int_V \frac{1}{\mu_r}(\nabla \times \mathbf{E}) \cdot (\nabla \times \mathbf{E}) - k_0^2\varepsilon_r \mathbf{E} \cdot \mathbf{E}\, dv + \frac{jk_0}{2}\int_{A2} (\hat{n} \times \mathbf{E}) \cdot (\hat{n} \times \mathbf{E})\, ds + \int_{A2} \mathbf{E} \cdot \mathbf{U}\, ds \quad (3)$$

Initially, **U** is calculated from eqn. 2 on the assumption that **E** in eqn. 2 is the same as the incident electric field $\mathbf{E}_{inc}$. Using the typical FEM procedure, with the functional in eqn. 3 minimised, the electric fields can be determined at any point. From these calculated fields, the equivalent magnetic current source on the aperture surface A_1 is introduced using the equivalence theorem, and this source generates the fields on the radiation boundary surface using the free space Green function by image theory. Since these generated fields are scattered fields, the total fields on the boundary surface are the sum of these scattered fields, the incident fields and the fields reflected by a PEC ground plane.

In this way, the fields on the radiation boundary are updated, which corresponds to updating the residual term **U** in eqn. 2. By iterating this procedure several times, the fields converge to an exact solution without internal resonance.

In this procedure, since the system matrix generated by this method is sparse and does not change during the iterations, the computational efficiency can be greatly enhanced.

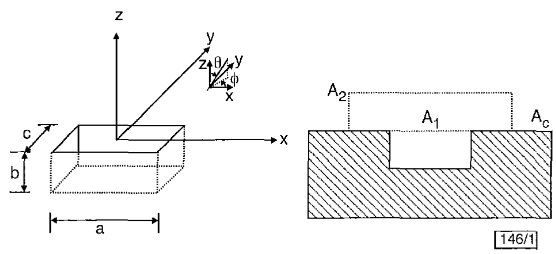

Fig. 1 *Geometry of cavity-backed aperture in ground plane and domain of analysis with fictitious boundary surface* A_2

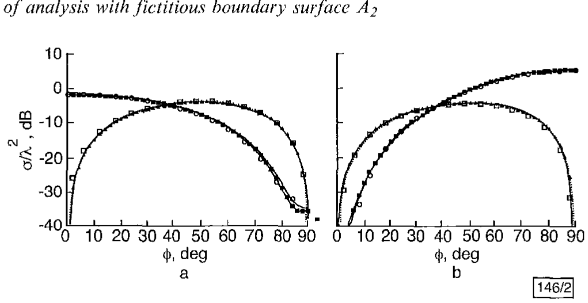

Fig. 2 *Monostatic RCS patterns for empty cavity against incidence angle*

$a = 0.7\lambda$, $b = 0.1\lambda$, $c = 1.73\lambda$, $\theta = 40°$
a $\mathbf{E} = \hat{\phi}E_\phi$
b $\mathbf{E} = \hat{\theta}E_\theta$
—■— proposed solution, co-polarisation
—▲— proposed solution, cross-polarisation
———; – – – – FEBIM solution
○; □ MoM/modal solution

Numerical results: To show the validity of this method, we analysed the scattering from a three-dimensional rectangular cavity-backed aperture in a ground plane. Fig. 2 shows the co-polarised and cross-polarised monostatic RCS of a deep empty cavity as compared with the data obtained via the FEBIM and MoM/modal approach [6]. The results are in good agreement.

Acknowledgment: This work was supported by the Brain Korea 21 Project.

11 July 2000
Electronics Letters Online No: 20001113
DOI: 10.1049/el:20001113

Jongkuk Park, Heeduck Chae and Sangwook Nam (*School of Electrical Engineering, Seoul National University, Seoul 151-742, Korea*)

References

1 JIN, J.M.: 'The finite element method in electromagnetics' (Wiley, New York, 1993)
2 ROY, T., SARKAR, T.K., DJORDJEVIC, A.R., and SALAZA, M.: 'A hybrid method for terminating the finite element mesh (electrostatic case)', *Microw. Opt. Technol. Lett.*, 1995, **8**, (6), pp. 282–287
3 ROY, T., SARKAR, T.K., DJORDJEVIC, A.R., and SALAZA, M.: 'A hybrid method solution of scattering by conducting cylinders (TM case)', *IEEE Trans. Microw. Theory Tech.*, 1996, **MTT-44**, (12), pp. 2145–2151
4 PARK, J., CHAE, H., and NAM, S.: 'An efficient hybrid method for characterisation of arbitrary-shaped discontinuities in a rectangular waveguide', *Electron. Lett.*, 1999, **35**, (14), pp. 1170–1172
5 PARK, J., and NAM, S.: 'Analysis of arbitrary shaped crosssectional discontinuity in rectangular waveguides using FEM-BIM with triangular prism elements'. IEEE AP-S Int. Symp., Montreal, Canada, 1997, pp. 672–675
6 JIN, J.M., and VOLAKIS, J.L.: 'A finite element-boundary integral formulation for scattering by three-dimensional cavity-backed apertures', *IEEE Trans. Antennas Propagat.*, 1991, **AP-39**, (1), pp. 97–104

Colour filtering using local density information

A. Fotinos, S. Fotopoulos and E. Zigouris

A multichannel filtering technique is proposed based on local density estimation. The window data are ordered according to their distance from that of the maximum density, and the samples to be averaged are selected using the Fisher discriminant criterion. The method has been evaluated in several real images.

Introduction: Signals like colour images, seismic signals, etc. that are described by more than one parameter are known as multichannel signals. A colour image consists of three channels which define a three-dimensional space (colour co-ordinate system). Among the several colour spaces [1], the most widely used is the RGB (red, green, blue) space. Conventional techniques for colour images, process each component separately but this approach generates new colours, especially when edge regions are processed. The situation is improved when vector techniques are employed. The colour image pixels in that case are treated as vectors with components corresponding to the values of the corresponding colour co-ordinate system channels (e.g. RGB). Several algorithms for processing colour images using the vector approach have already appeared in the literature [2, 3].

In this Letter, it is assumed that an image consists of homogeneous and non-homogeneous regions. The homogeneous region could be treated as one class structure, while the nonhomogenous region as two classes. The aim of this Letter is to select the samples which belong to the major class i.e. the class with the maximum density value. The proposed filter is based on ranking the multichannel data in the *p*-dimensional space R^p (in our case p = 3) according to their distance from the vector with the maximum density X_M. This technique places the vectors which are close to X_M in the lower ranks, while the outliers or/and vectors which belong to the other class are placed in the upper ranks of the sorted data. Subsequent use of a discriminant function selects the samples which belong in each class (i.e. for the case of the two