Behavioral testing of cellular neural networks

Citation for published version (APA):

DOI:
10.1109/ISCAS.1994.409569

Document status and date:
Published: 01/01/1994

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
BEHAVIORAL TESTING OF CELLULAR NEURAL NETWORKS

John Willis and José Pineda de Gyvez
Department of Electrical Engineering,
Texas A&M University, College Station, Texas 77843-3128 USA

Abstract
This paper addresses the functional behavior of Cellular Neural Networks (CNN). The impact of variable convergence times on the proper operation of the network is discussed. A test method is presented to determine the functionality of the network. The function fault models assume that the cells are unable to switch between limiting states. The proposed method attains 100% stuck-at fault coverage without any extra hardware for its implementation. Moreover, the required number of test vectors is constant and independent of the array size which makes it suitable for practical implementations. The paper discusses the new fault model, presents the algorithmic procedures and shows simulated testing results.

Introduction
The converged final state of a Cellular Neural Network relies on the interaction between cells as determined by the templates. Some applications depend on the output value of cells to determine the final state of the Network. This paper will look at the effect of variances in the convergence rate of cells and its impact on the final state of the Network.

The testing of CNNs has been scarcely addressed. The only existing approach has limited applications such as only orthogonal interaction with neighboring cells is tested and it requires additional hardware to implement [1]. The test described in this article overcomes the previous limitations and achieves 100% fault detection. Using the concept of C-Testability, it is possible to determine the functionality of a processing array by applying a constant number of predetermined vectors independent of the array size and then comparing the actual output values to the predicted output values [2]. Under C-Testability, the input is propagated through the network to arrive at a final output state. If the actual final state is the one predicted by the given input vector, then the network is determined to be operating properly. However, if a given cell is faulty, its faulty state value will also be propagated and the fault will appear at the output.

Background
A CNN is an analog cellular nonlinear dynamic processor array. The basic circuit unit is called the cell [3,4]. It contains linear and nonlinear circuit elements. Any cell, C(i,j), is connected only to its neighbor cells, i.e. adjacent cells interact directly with each other, see Fig. 1. This intuitive concept is called neighborhood and is denoted as N(i,j).

Cells not in the immediate neighborhood have an indirect effect because of the propagation effects of the dynamics of the network. Each cell has state x, input u, and output y. The state of each cell is bounded for all time t > 0 and, after the transient has settled down, a cellular neural network always approaches one of its stable points. The dynamics of a cellular neural network have both output feedback (A) and input control (B) mechanisms. The first order nonlinear differential equation defining the dynamics of a cellular neural network is shown by (1).

\[
\frac{dx(t)}{dt} = -\frac{1}{R_x}x(t) + \sum_{c(k,m)=N(i,j)} A(c,k) y(c,k) + \sum_{c(k,m)=N(i,j)} B(c,k) u(c,k)
\]

With border cell inputs

Fig. 1 Cellular Neural Network 4 x 4 processing array with border cell inputs

A set of inputs is necessary to simulate interaction with imaginary cells outside the processing array to insure that the cells on the perimeter of the processing array achieve proper convergence. These imaginary cells are called border cells and form a ring around the processing array. A border cell, such as border cell C(0,0) of Fig. 1, outputs a constant voltage to mimic the output voltage v_p that a properly converged cell would produce as well as a voltage v_i to represent the input image voltage that border cell C(0,0) would receive if it were a functioning cell. Therefore, a cell on the perimeter of the processing array uses the image voltage and dynamic output voltage of neighboring cells as well as the static output and image voltages of the border cells to arrive at the proper final state. The border cells are treated as members of the array for initialization purposes and template implementation, but are not considered in the final state analysis.

Convergence Variance
Cell convergence is achieved when \( \frac{dx(t)}{dt} = 0 \). The rate of convergence is determined by many factors. The amount of current that is flowing into the cell, as governed by the templates, determines if the cell converges at its maximum rate. \( \tau \) is defined as the amount of time it takes for the state of a cell to change from its most positive state to its most negative state. The maximum convergence rate of a cell C(i,j) is determined by C the capacitor as defined in (1), and the equivalent resistance, \( R_{eq} \), seen by C. If another cell C(m,n) in the CNN has a variance in either C or \( R_{eq} \) the result will be a change in \( \tau \), defined as \( \Delta \tau \).
The proper final state of a CNN can vary depending on $\Delta \tau$. If the output of a cell is used to determine the final state of a CNN, as is the case when $A \neq 0$, then it is possible that the cells can converge to a wrong value. The dependence of a CNN on $\Delta \tau$ is determined by the architecture of the array as well as the templates used to implement the given function.

If the CNN relies heavily on the $B$ template, then the effect of $\Delta \tau$ is minimal. This is because the network is being driven by the constant value of $a_{ui}$ representing the image which can offset any slowly converging cells.

The architecture used to implement a CNN can also increase the effects of $\Delta \tau$. If the slope of the nonlinear output limiting function $f_T(\cdot)$ is very steep, then the effects of $\Delta \tau$ are greatly increased. A very steep slope implies that the output, $y$, of a cell changes very rapidly when the value of the state, $x$, is close to the origin. Therefore, at some point in time, say $\tau$, the output of the cell changes very rapidly from $-1$ to $+1$ without the cell being fully converged. If a cell $C(i,j)$ has a convergence time of $\tau + \Delta \tau$, then using the same assumption, the output changes at time $\frac{\tau + \Delta \tau}{2}$. If cell $C(i,j)$ is surrounded by cells with the quicker convergence time of $\tau$, then the outputs of the surrounding cells change states before cell $C(i,j)$.

If the output of cell $C(i,j)$ is dependent only on the output of the cells surrounding it, then the final state of cell $C(i,j)$ is effected by the improper data that it receives in the time period between $\frac{\tau}{2}$ and $\frac{\tau + \Delta \tau}{2}$. The following simulation results show this effect.

A 5x5 CNN was simulated using HSPICE. The template multipliers were voltage controlled current sources. The output function $f_T(\cdot)$ was implemented using a transistor level inverter. The slope of the output function is very steep as discussed above. The output, $y(t)$, transition from the negative rail to the positive rail takes place when the state, $x(t)$, is between $-10mV$ and $+10mV$.

An edge detection template was used on the diamond image of Fig. 2a. The initial conditions placed on the cells are the values for the pixels of the image itself. A black pixel is represented by a normalized value of $-1$ volt and white pixel is represented by a normalized value of $+1$ volt. The simulation was run with all cells having the same value of $\tau$ with $C=1.5pF$. The correct final state of the processed image is shown in Fig. 2b.

The $\Delta \tau$ of cell $C(3,3)$ was then altered by changing the value of the capacitor in the cell to $1.05C$. This had the effect of making $\Delta \tau$ equal to $5\%$. Fig. 2c shows that the slower convergence rate of cell $C(3,3)$ caused the CNN to converge to an improper final state.

**Fig. 2** Edge detection using initial conditions

\[ a \] input image

\[ b \] final results with $\Delta \tau = 0$

\[ c \] final results with cell $C(3,3)$ having $\Delta \tau = 5\%$

Fig. 3 shows a comparison between the state of cell $C(3,3)$ and its surrounding cells. As the figure shows, at $1.7us$ cell $C(3,3)$ has decayed to $.4V$ but the surrounding cells have already reached the transition point. Once the surrounding cells reach the transition point, their output changes to $-1$. This change causes the surrounding cells to inject current into cell $C(3,3)$. The injected current causes the state of cell $C(3,3)$ to begin to rise. The graph shows the impact of this change on the cell.

**Fig. 3** State value comparison with cell $C(3,3)$ having a slower convergence time. The state of cell $C(3,3)$ is shown as the dashed line and the state of all surrounding cells is shown as the solid line.

**Convergence Test Method**

The test method presented next test a CNN for variances in convergence. The test is intended to be used in a production environment in conjunction with the functional test presented in the following sections. The test uses an edge detection type template to detect slowly converging cells. After the test, the slow converging cells appear black while the rest of the array turns white. The convergence test algorithm is presented next.

1. Let $A = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 \\ -1 & 4.5 & -1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$ $B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$ $I = -4.7$

2. Set the input image and border cells to black $\forall_{ij} a_{ij} = 1$ $i = 0,1,...n + 1$ $j = 0,1,...m + 1$

3. Set the initial conditions to black $\forall_{ij} x_{ij}(0) = -1$ $i = 1,2,...n$ $j = 1,2,...m$

4. Allow the CNN to converge

5. All cells, $C_{ij}$ remaining at black are considered slow to converge $\forall_{ij} x_{ij} = -1 \rightarrow C_{ij}$ $i = 1,2,...n$ $j = 1,2,...m$

The test works much in the same way as edge detection. The test image is a solid black box with the border cells forming the edge of the image. The initial conditions placed on the cells cause the dynamic convergence of the array to drive the cells to their final steady state. Cells which are slow to converge remain at black as discussed in the above example. The test can detect variances in $\Delta \tau$ as small as $5\%$ as long as the cell does not have two or more slowly convergent orthogonal neighbors.

**Simulated Convergence Test**

A 5x5 CNN simulator implemented using HSPICE was used to confirm the above test procedure. All cells had a $1pF$ integrating capacitor except for cells $C(1,1), C(2,3), C(2,4)$,
and cell \(C(5,4)\) which had a capacitor value of 1.05pF. This resulted in a \(\Delta t\) of 5%.

Fig. 4  Slow converging cells
a original test image to be processed
b final result showing cells \(C(2,3), C(2,4)\) and cell \(C(5,4)\) are slow converging cells

As Fig. 4 shows, all slowly convergent cells remained black except cell \(C(1,1)\). This is due to the fact that this cell had the constant driving force of the border cells to eventually force the cell to a white value. This is similar to the effect of having the \(B\) template present. Fig. 5 shows the state value of cell \(C(1,1)\). The convergent rate of the cell is slowed when its neighbors outputs change, but its direction is not reversed. Due to this phenomenon the corner cells of the array will always converge to the proper value.

![Image](image_url)

Fig. 5  State variable value of cell \(C(1,1)\) showing the effect of the border cells on its convergence. The state of cell \(C(1,1)\) is shown as \(-1\) and its output is shown as the solid line

Fault Models

A CNN processor has only two output states. Commonly, in image processing applications these states appear as white or black pixels. If a cell is unable to change from one state to the other, it is defined to be “stuck-at-white” or “stuck-at-black”, depending on its current value. With the proposed test method it is possible to detect 100% of the stuck-at faults in the processor.

Functional Test Methods

The test procedure has two separate methods to detect faulty cells, a local method using the \(B\) template and a propagation method using the \(A\) template. The entire array can be tested using either of these methods regardless of its size. The advantage of the \(A\) template method is that it verifies that each cell is responding correctly to its neighbors without having to disseminate information throughout the network properly.

The local method uses the input image and the \(B\) template to predict the final output state, \(y_{ij}\), of each cell in the array. The algorithm for the local test procedure is shown next. The normalized value corresponding to a white input is \(-1\). The \(B\) template values are also \(-1\). The positive product of these two values results in current being injected into cell \(C(i,j)\)

1. Let \(A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\)
2. Set the input image and border cells to white \(V_{ij} u_{ij} = -1 \ i = 0, 1, \ldots, m + 1 \ j = 0, 1, \ldots, n + 1\)
3. Set the initial conditions to white \(V_{ij} x_{ij}(0) = -1 \ i = 1, 2, \ldots, n \ j = 1, 2, \ldots, m\)
4. Allow the CNN to converge
5. All cells, \(C_{ij}\) remaining at white are considered faulty \(V_{ij} y_{ij} = -1 \rightarrow C_{ij}\) is faulty \(i = 1, 2, \ldots, n \ j = 1, 2, \ldots, m\)

The process starts at the left edge of the array and propagates across the network to the right side. Since the border cells, \(C(0,j)\) are black, the predicted result should be an all black image. If a “stuck-at-white” fault is detected, then all properly functioning cells to the right of the stuck cell should also remain white. The faulty cell in effect casts its “shadow” across the array. The situation where two or more faulty cells lie on the same row can be detected by rotating the \(A\) template clockwise 45° and repeating the test. The template should be rotated in this manner 360° in order to assure complete
coverage of the array. The “stuck-at-white” cells can be
determined by performing the logical OR of the resulting
eight output images. The same procedure can be used to
detect “stuck-at-black” cells by changing all occurrences of
white to black and -1 to 1 in steps 2 thru 8 in the propagation
test algorithm and performing a logical AND in step 7.

Simulated Functional Test Results
Using a CNN simulation program the above tests were
applied to a 5x5 CNN network. In both the local and
propagation tests, cells C(3,2) and C(2,3) were intentionally
forced into the “stuck-at-white” state. Fig. 6a shows the
input image used for both tests. Fig. 6b shows the resulting
final image after the simulation of the local test. It is clearly
seen that all properly working cells have successfully
implemented the B template and made the transition from
white to black. Cell C(2,2) was able to make the transition
even though two of its neighbors where faulty. This is
because the output of each cell is due only to the input image
and is independent of any cells output.

Fig. 7 shows the results of the simulation after the
propagation test. Fig. 7a shows the “shadow” effect
discussed earlier. It is safe to assume by viewing Fig. 7a that
cells C(3,2) and C(2,3) are faulty. However, it is unclear if
any of the remaining cells on rows 2 or 3 are
“stuck-at-white” due to the “shadow” of the faulty cells.
Fig. 7b shows the result after rotating the template 45° and
the new direction of propagation. It is still unclear as to
whether cell C(3,4) is functioning properly. Fig. 7c confirms
that cell C(3,4) is functioning properly.

Fig. 6 Local test method
a input image
b final result
For this example, ORing the three images of Figs. 7a–c is
easy to show all faulty cells. In more complicated fault
location patterns however, the template must be rotated
completely to detect all possible faults. The results of the test
are shown in Fig. 7i and it is clear that cells C(5,2) and C(2,3)
are faulty.

Fig. 7 Propagation test clockwise template rotation
a 0° b 45° c 90°
d 135° e 180° f 225°
g 270° h 315° i final result

Conclusion
The variance in convergence rates of the cells of a CNN has
been shown to have an impact on the final state of the
Network. If cell C(i,j) is slower to converge to its final state
than the cells around it and if the architecture is sensitive to
variances in τ, then cell C(i,j) may fail to make the transition
to its proper final value. A convergence test method to detect
dependence on Δτ has been proposed. The test method can
detect variances in convergence rates as small as 5%.

A testing method for CNNs has been presented which
provides 100% fault detection with no additional hardware
required. Only five input vectors are needed x(0), u, A, B and
I. The image vector u contains only two components, the
color of the image and the color of the border cells. The
initial conditions are always the same color for the entire
array therefore the vector x(0) needs to only represent the
color chosen. The template vectors A and B always contain
the nine values necessary to interact with the surrounding
cells of C(i,j). I, the independent current source vector is 0
in all cases. Since none of the input vectors have any
dependency on the array size, any size array can be tested and
the number and size of the input vectors will remain constant.

Both functional testing methods give 100% fault detection.
The local testing method provides 100% fault isolation and
the diagnosis is available by simply looking at the final
image achieved after the CNN converges. There are some
fault location configurations that could impede fault
isolation using the propagation test, i.e. if the faults form a
complete rectangle, the status of the cells inside the rectangle
would be unknown due to the shadow effect. This fact
lowers the fault isolation capabilities of the propagation
method but, does not change the fault detection percentage.

The diagnosis for the propagation test is available after the
A template has been rotated 360° and the proper logic
function has been performed on the results.

References