Spatiotemporal pattern formation in the ACE16k CNN Chip

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***Abstract*— In this paper, pattern formation occurring on the ACE16k CNN chip is presented. The CNN chip can be programmed with a cloning template in order to generate spiral waves and autowaves. The waves diffract from the *internal sources* which cannot be relocated on the network. However, by using initial and/or input images, sources (*external sources*) can be located at any place on the network. Furthermore a competition between autowaves generated by external and internal sources is observed. Propagation of autowaves on the inhomogeneous CNN array, formed by the fixed-state map, is presented.**

I. Introduction

Autowaves are a particular class of nonlinear waves resulting from strongly nonlinear active media [1]. The fundamental properties of autowaves are

- the shape and amplitude of autowaves remain constant during the propagation,
- they do not reflect at the medium boundaries,
- two colliding autowaves annihilate.

The CNN framework provides a very useful tool for studying spatial-temporal pattern formation [2], [3], [4]. Autowaves are well described by reaction-diffusion equations. As a result the reaction-diffusion CNN model has been widely used to generate such waves. In [1], Munuzuri *et al.* have presented a review on the study of spatial-temporal behaviors on an array of Chua's circuits, where Chua's circuit is used as the reaction term in the model. In [3], Manganaro *et al.* have used a second-order system for the reaction term and have observed autowaves, spiral waves and Turing patterns. In fact, the model used by Manganaro *et al.* [3] can be thought of as a two layer CNN with a Chua-Yang model. In [5], a VLSI implementation of a two layer CNN with Full-range CNN model (CACE1k) has been experimentally verified spatial-temporal phenomena on CNNs. An experimental observation of autowaves on a ACE16k chip is shown here. The first experimental observation of these phenomena on a ACE16k chip has been given by Yalçın *et al.* in [6] and [7].

This paper is organized as follows. Section 2 shortly describes the ACE16k chip. Section 3 presents pattern formation on an ACE16k chip. Section 4 presents propagation of autowaves on the inhomogeneous CNN array which is formed by the fixed-state map.

II. ACE16 CNN Chip

Analogic Cellular Engines (ACEs) are designed based on the CNN-Universal Machine (CNN-UM) architecture. They are capable of realizing a very large variety of image related spatial-temporal operations and algorithms through the execution of a suitable sequence of instructions (or templates). The ACE16k chip is the third generation of ACE chips and it consists of an array of 128×128 identical analog Full-range CNN cells. Complex dynamic behaviors in Full-range model have been studied in [8] and a strange attractor similar to the chaotic attractor observed in a CNN with Chua-Yang model has been observed. An experimental observation of similar chaotic attractors in ACE4k [9] has been reported for an asymmetric template class in [10]. For information on the ACE16k chip, we refer to [11] and [12].

III. Experiments

For the discussed experiments, the vector of the recommended settings of the internal references (<hwparams>) is set to [0 0 0 229 200 172 145 109 78 37 23] [13]. The internal references include optical, weight and signal references which are setting currents and voltages for the specific blocks in the ACE16k. The current and bias which define the threshold z are set to 0. Furthermore, a fixed boundary condition with 0 was used during our experiments.

A. Experimental results: Autowaves

In the first experiment, the following templates

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (1)$$

were chosen and a full white image was used for initial and for input. Figure 1 shows several snapshots depicting the obtained autowave during the time evolution for the cloning template (1). There are four wave sources in Figure 1 (a) which are located at the corners. These are called *internal sources* because it has been observed that these sources stay active during the different experiments. The waves in Figure 1 (a)show the fundamental properties of autowaves: two waves spreading in opposite directions do not pass each other (as is usual for the classical conservative waves) but mutually

annihilate. Also the shape and amplitude of the waves remain constant during propagation and the waves do not reflect at the boundaries of the network.

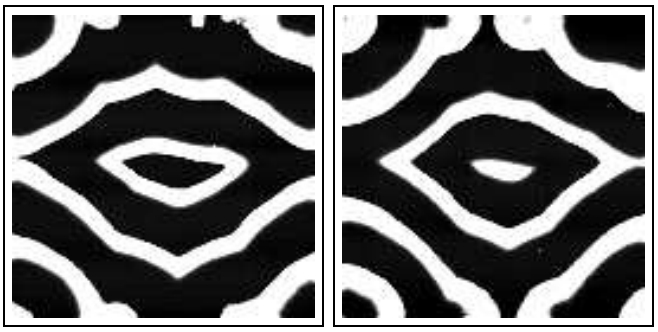

Fig. 1. (a-b) The time evolution for the cloning template (1). Each snapshot has been obtained by executing the same template with the same input and initial state but running time was increased as much as time stamp between the snapshots. The waves diffract form the corners. The shape and amplitude of the waves remain constant during propagation. There are no interferences between waves but the colliding waves annihilate. Furthermore the waves do not reflect from the boundaries of the network.

In a second experiment, it is shown that new autowave sources which is called here as *external sources* can be located in any place on the network. A source can be located with black dots on the initial and input images. In Figure 2(a) (the box around the figure is not a part of the image) a source is located on the left-bottom corner. Two consecutive snapshots depicting the obtained autowave in time. One can clearly see two autowave sources in Figure 2(b). While one of them is the *internal source* of the network, the other is located where the black dot is placed on the initial and input images. This experiment has been also repeated for four sources which are placed at the corners (see Figure 2(d)). The result is shown in Figure 2(e) and a consecutive frame is shown in Figure 2(f). Figures 2(e) and (f) clearly shows that the waves diffract from the defined sources. They interact approximately in the middle of the network and then annihilate each others.

Figure 3 shows the competition [1] between the autowaves which are generated by four internal sources and one external source. Initially the waves from the external source and internal sources start interacting and then annihilate (see Figure 3(a)). The region where they interact and annihilate is drifting towards the right-top corner of the network. Figures 3(a-f) show successive snapshots on the network during the competition. A movie file for whole time evolution can be seen in `http://www.esat.kuleuven.ac.be/~mey/NLab/autowaves/test2.avi`. This competition because of the autowaves from internal sources emits with a frequency higher than the frequency of the autowaves from the external sources.

B. Experimental results: Spiral waves

In a next experiment, we use the following templates

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2)$$

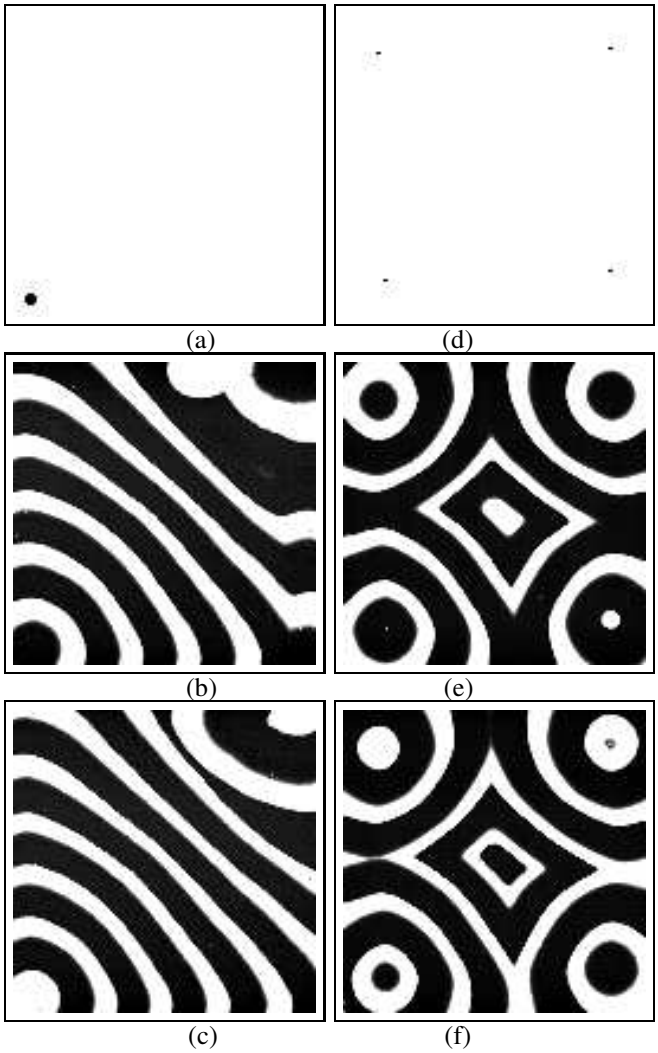

Fig. 2. (a,d) Initial and input image (the box around the figure is not a part of the image). (b-c) and (e-f) evolutions in time for the cloning template (1) corresponding to the initial and input images from (a) and (d), respectively.

which has the same feedback template as the previous experiment. However it includes a zero central element in the control template. Figure 4(a) shows the obtained result with a full white image as initial condition. The network has two internal spiral wave sources at the left and right side of the image. Using the given initial conditions in Figures 4(b) and 4(c), external sources for spiral wave can be located on the network as shown in Figure 4(d) and (e).

IV. Propagation of autowaves on the inhomogeneous CNN arrays

The fixed-state map of a CNN is a binary image *e.g.* Figure 5(c-e), specifies which CNN cells are in an active or inactive state for all time. The state variables of these cells are frozen to fixed values and do not change in time. Therefore, the fixed state option offers an inhomogeneous structure for the CNN array. The ACE16k CNN chips allow this fixed-state map.

In our first experiment, the network has been divided into two sub-networks using the fixed-state which is given in

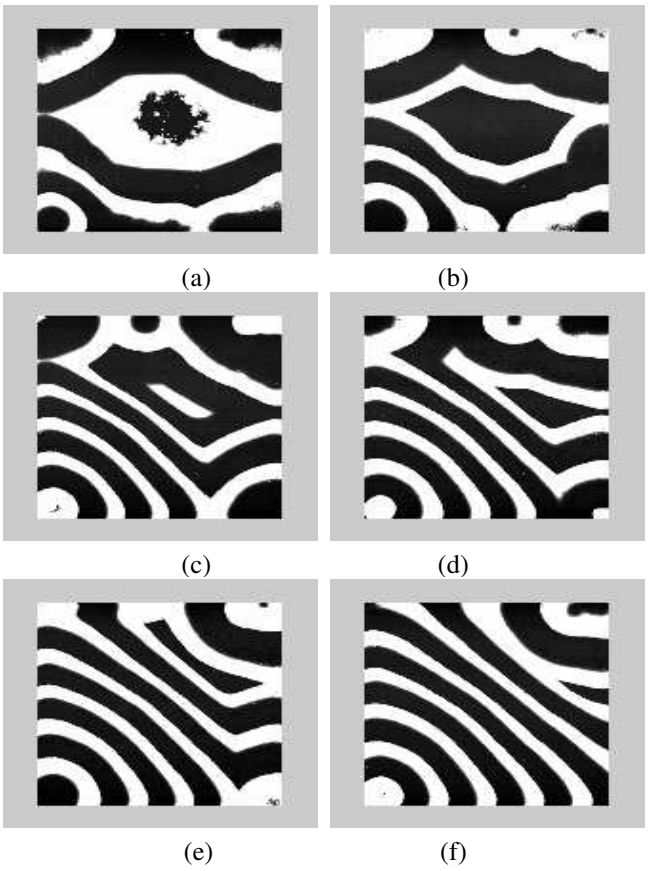

Fig. 3. Competition between autowaves resulting from the chip-internal sources and an autowave resulting from an externally imposed source. The interaction region of the autowaves moves to the right-top corner of the network.

Figure 5(c). In order to see the propagation of autowaves on these two sub-networks, Figure 5(a) has been chosen as an initial and input images and template (1) has been used. As expected, one external autowave source is located on the each sub-networks. There is also no interference between the autowaves propagated from external sources because of the isolation by the fixed-state (see Figure 5(f)). However there is an interaction between the waves propagated from the external source and the internal sources on the same sub-network which is at the right hand side of the network.

In a second experiment, Figure 5(d) has been used as a fixed-state map and Figure 5(b) has been taked as an initial and input images. In this experiment we have observed that the waves propagated from the external source can pass through the opening on the array (see Figure 5(g)). Experimentally it has been verified that if there are at least three cells active (or not fixed), waves can pass through the opening.

The experiment has been repeated with the fixed-state for Figure 5(e). Figure 5(h) shows that the waves propagate to the right on the inhomogeneous CNN arrays. The waves from the internal source propagate from the opposite direction. We can also see a competition between external and internal sources in the inhomogeneous network.

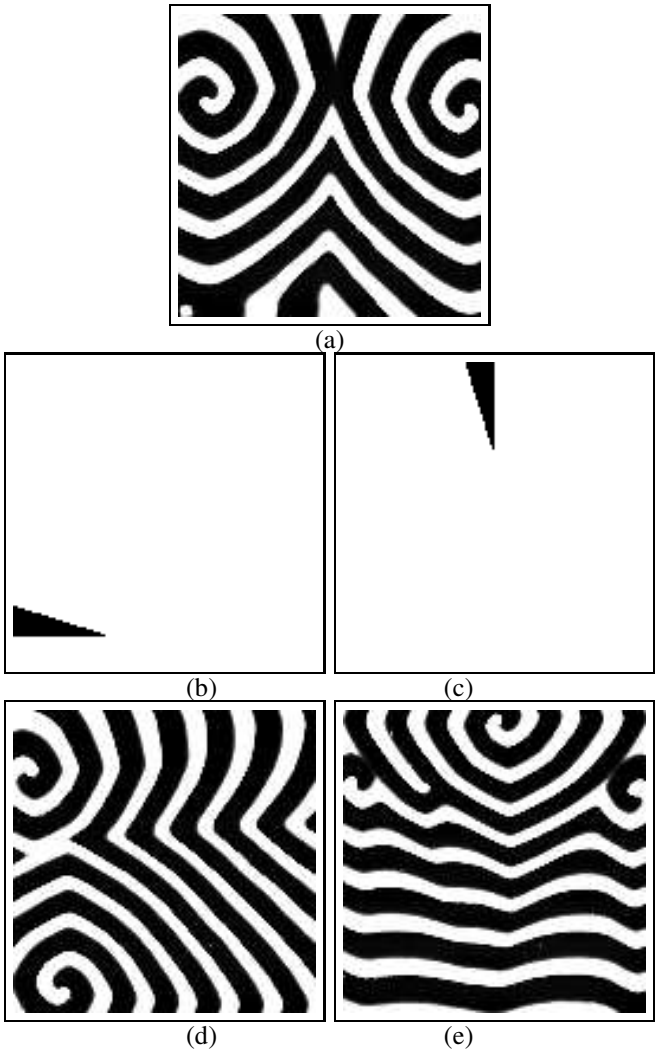

Fig. 4. (a) Spiral wave obtained on the ACE16k chip for a full white image as initial image. (b)(c) two different initial images. (d)(e) spiral waves obtained for the initial states (a) and (b), respectively.

V. Conclusions

The erroneous behavior observed in VLSI implementations of CNN causes unavoidable and undesirable features which make CNN chips loose reliability for certain template operations [14]. Here we have taken advantage of these undesirable features in order to generate complex phenomena on the VLSI implementation of CNN *i.e.* ACE16k. Although the chip has internal spiral and autowave sources which cannot be relocated on the array, we have shown that external sources can be defined and relocated anywhere on the array. Furthermore we have presented propagation of autowaves on the inhomogeneous CNN array formed by the fixed-state map. These phenomena can be further employed towards applications such as e.g. path finding in labyrinths.

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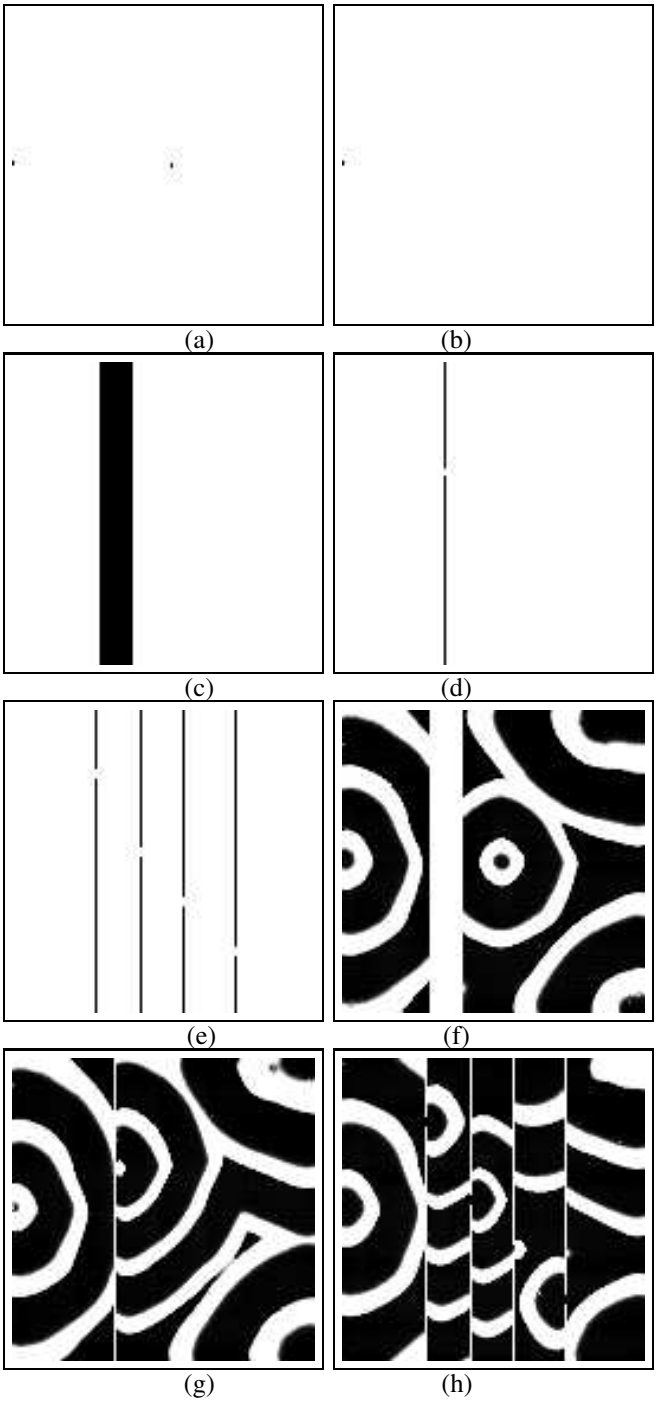

Fig. 5. (a,b) Images which are used as initial and input images. (c-e) examples of different fixed-state maps. The black regions have state variable values that are fixed in time. (f-h) Propagation of autowaves on the CNN corresponding fixed-state (c-e) using the same initial and input images of (a) for (f) and (b) for (g-h), respectively.

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