A Few Applications of Digital Image Processing Based on Two-Dimensional Cellular Automata

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Abstract : Cellular Automata (CA) is a technique that uses discrete space and time to represent the state of picture elements of a digital image and the state for the next time-step can be changed according to a transition rule or function. In this research work, binary images are considered and the space of rule sets is still very large. Here, we have tested all the Linear Rules (LR's), uniform as well as hybrid of our proposed Two Dimensional Cellular Automata (2D CA) model for a range of image processing tasks like translation, pattern generations, reflection, edge detection, noise filtering and thinning of digital images. Several modifications to the standard CA formulation are proposed, that improves performance significantly. The paper is organized as follows: Section 2 deals with the introduction to basic concepts of CA. Section 3 deals with the proposed implementation technique for digital image processing. Section 4 shows the experimental results and discussions. Finally, Section 5 provides the conclusions and perspectives of this work.

***IndexTerms* - Cellular Automata, Image processing, Translation, Pattern generation, Reflection, Edge detection, Noise filtering, Thinning.**

I. INTRODUCTION

CA are a class of very powerful models originated in Computer Science and used as a discrete model for implementing algorithms. They are well known extensions of the classical automata. This basic theory of the classical CA was established by John Von Neumann [1]. Later, Stephen Wolfram developed the theory [2]. The name CA is widely used to describe new modeling methods, often even for methods that do not fulfill some of the elementary conditions imposed by the definition of CA. Many versions of CA with three-neighborhood local state transition rule are known. In [3], algebraic properties of CA with local state transition rule number 90 are investigated. In [4, 5], properties of CA's with cyclic boundary condition are investigated using a polynomial expression. These studies mainly deal with three neighborhood CA's. But the behavior of CA's with five or more neighbors is full of variety [6]. Even without the specialized hardware implementations that are available, the running time of the CA is moderate. At each iteration, if there are P pixels, and a neighborhood size of N (where N is 9 and 25 in this study), the computational complexity is O(PN).

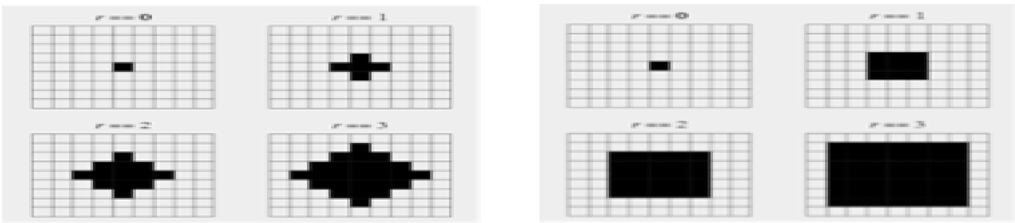
There has been made a lot of effort in designing efficient rules for digital image processing based on 2D CA. In [7], authors have reported some empirical studies on 2D CA depending on five neighborhood CA. In [8], authors have extended the theory of 1D CA that is built around matrix algebra for characterizing 2D CA. In [9, 10], authors have studied the nine neighborhood 2D CA model. They developed the basic mathematical model to study all the nearest neighborhoods of 2D CA and presented a general framework for state transformation. However, emphasis was laid on special class of additive 2D CA, known as restricted vertical neighborhood CA. In this class of 2D CA the vertical dependency of a site is restricted to either the sites on its top or bottom, but not both. Characterization and applications of some particular uniform and hybrid 2D CA LR's are reported in [11]. In [12], authors have studied the evolution of CA for image processing- focusing mainly on edge detection and thinning. Later, authors have proposed modeling techniques for fundamental image processing [13]. Recently, [14, 15] gives the theory and applications of 2D nine neighborhood null boundary, with uniform as well as hybrid CA LR's in image processing. These rules were classified into nine groups and mostly applied on symmetric binary images.

In this study, we utilize different configurations of 2D CA with local neighborhood interconnection to study digital image processing techniques. Here, we use the LR's (uniform as well as hybrid) of our proposed 2D CA model for a range of image processing tasks like translation, pattern generation, rotation, noise filtering, edge detection and thinning of black regions. A very important feature of the proposed methods is their intrinsic parallelism, since they are implemented on well-known parallel-working machines, as CA's are. This provides the potential (when implemented appropriately) to make the proposed methods faster as compared to the other methods.

II. CELLULAR AUTOMATA

CA are a class of very powerful models originated in computer science and used as a discrete model for implementing algorithms. In recent years, CA have been found as an attractive modelling tool for various applications which invites computer scientists, chemists, biologists, mathematicians and physicists on a common platform. The main purpose of this study is to investigate the potential of applying CA to digital image processing. A 2D CA is especially suitable for application to pixel-level processing because an image has a two-dimensional topology. Also, the ability to obtain complex behaviour from simple local rules makes 2D CA an interesting platform for digital image processing.

The structure of the neighbours mainly includes Von Neumann neighborhood and Moore neighborhood [20], as shown in Figure (1):



(a) (b)

Fig.(1): Structure of the neighbourhoods; (a) Von Neumann, (b) Moore

Von Neumann Neighborhood: The Von Neumann neighborhood of a 2D CA is a diamond shaped neighborhood surrounding the cell (*i, j*) and can be defined as follows:

$$V_N(i,j) = \{(k,l) \in L : |k - i| + |l - j| \le r\}$$

Moore Neighborhood: The Moore neighborhood of a 2D CA is a square shaped neighborhood surrounding the cell (*i, j*) and can be defined as follows:

$$M_N(i,j) = \{(k,l) \in L : |k - i| \le r, |l - j| \le r\}$$

III. PROPOSED METHODOLOGY

To perform digital image processing based on 2D CA means applying simple rules that leads remarkable behaviours. A rule is the "program" that governs the behaviour of the system. All cells apply the rule over and over, and it is the recursive application of the rule that leads to the remarkable behaviour exhibited by many CA's. In 2D CA twenty-five neighborhood CA the next state of a particular cell is affected by the current state of itself and twenty-four cells in its nearest neighborhood also referred as extended moore neighborhood with r=2 as shown in Table-(1). A specific rule convention that is adopted here is given by [16, 17, 20].

The central box represents the current cell and all other boxes represent the twenty-four nearest neighbours of that cell. Each box contains the rule number as well as the pixel location associated with that rule. In case, the next state of a cell depends on the present state of itself and/or its one or more neighbouring cells (including itself), the rule number will be the arithmetic sum of the numbers of the relevant cell. Therefore, 2^{25} = 33554432 possible states exist. Each of 33554432 states can produce a 1 or a 0 for the centre cell in the next generation. Hence, $2^{33554432}$ possible rules exist. A comprehensive study of all rules in higher dimensional automata is thus not easily possible. However, in this paper we will mainly concentrate on few secondary rules of interest, i.e. the rules, which can be realized by EX-OR operation only

In order to provide the hardware implementation of our image processing study, we propose CA architecture in the form of Cellular Automata Machine (CAM) which, consist of memory elements for the storage of neighborhood cells, the combinational circuitry for the operations and a multiplexer for selecting the operation. In our proposed model, we have tried to exploit the regular, modular and cascadable structure and inherent parallelism of CA for image processing. On the basis of our proposed 2D CA model, the floor plan of the CAM consists of 2D array of cellular circuits (Pixel Circuits) is given as under [10, 17, 20].

65536	**32768**	**16384**	**8192**	**4096**
131072	**16**	**8**	**4**	**2048**
262144	**32**	**1 (i,j)**	**2**	**1024**
524288	**64**	**128**	**256**	**512**
1048576	**2097152**	**4194304**	**8388608**	**16777216**

Table (1): 2DCA Rule Convention using moore neighborhood

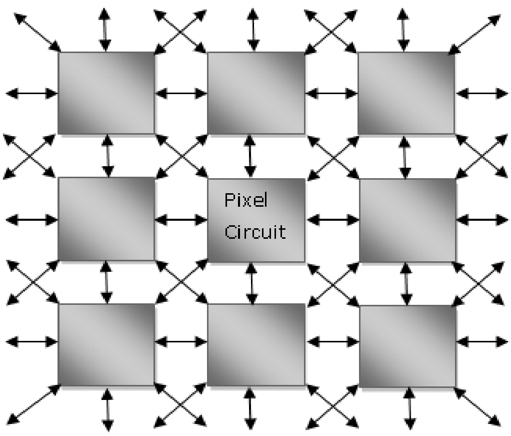


Fig. (2): Pixel Circuit

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Applying 2D CA LR's for translation, pattern generation and rotation, we take a binary matrix of size (256x256). Then we take the standard test image called the Lena image (Monochrome) whose size is (76x76) and put it in the center of the binary matrix. For other transformations the image is left as it is. This is the way, how the image is drawn within an area of (256x256) pixels, which we indicate by adding null boundary condition. We then apply 2D CA LR's on that (256x256) matrix after adding periodic boundary condition and each time the rule is applied using the changed matrix and a new image is redrawn. The various digital image processing techniques based on proposed 2D CA are given as follows:

Translation; Images are being processed and manipulated at every step in modern multimedia tools. In most gaming devices and cartoon series, movement of images are confined or restricted to right, left, up and down directions only [16]. With our scheme, we are not only able to translate the image into x and y-axis but also diagonal translations can be achieved. Uniform CA rules are constructed with periodic as well as null boundary condition to transform the images in all the directions, as illustrated in Figure-(3). Similarly these rules can also be applied for colour images [17], as the primary rules will be same for all types of images.

Fig. (3): Translation of image along +x, –x, +y, -y, top-left, top-right, bottom-left and bottom-right directions using Rule 32P, Rule 2P, Rule 128P, Rule 8P, Rule 256P, Rule 64P, Rule 4P and Rule 16P

Pattern Generation; Pattern generation is the process of transforming copies of the motif about the plane in order to create the whole repeating pattern with no overlaps and blank [18]. In our model, two states, i.e. black and white, are used to represent the state of cells. Therefore, the pattern is treated as the developing black and white patterns. The rules other than the fundamental rules generate different patterns of the given image. It is observed that the patterns can generate only when number of repetition is 2^n (n=1, 2, 3,…) [14, 15, 17]. The Figures from 4-11 illustrate the above assertion for n = 6, followed by periodic boundary condition.

Reflection; Two-dimensional reflections cannot be obtained by applying the primary rules to the given image again and again. However, combinations of the primary rules will yield the desired results (secondary rules). Here, we tested all the rules belonging to group2 under null as well as periodic boundary condition, as this group gives a pattern consisting of two images, as discussed in the above section. In order to obtain a mirror image of the given image along y-axis, we first apply rule 16P, 70 times and then rule 136N, 128 times. Similarly, to obtain a mirror image of the given image along x-axis, we first apply rule 64P, 70 times and then rule 34N, 128 times. The results are shown in Figure 12.

Noise Filtering; The next experiment is on filtering of digital images to overcome "Salt & Pepper" noise. We propose a dynamical rule which hopefully will solve our problem. The central pixel value of the neighborhood is updated by using Rule 480P (hybrid). The neighborhood is moved in the next location and update process is continued until the last location of the noisy image is reached and the result is shown in Figure 13. The proposed methodology can also be applied for greyscale images [20].

Edge Detection; An edge is a boundary or a contour at which a significant change occurs in some of the physical aspects of the image. In this section, we present a CA rule that can be used in the process of edge detection. The central pixel value of the neighborhood is updated using Rule 257P. The neighborhood is moved in the next location and update process is continued until the last location of the image is reached and the result is shown in Figure 14.

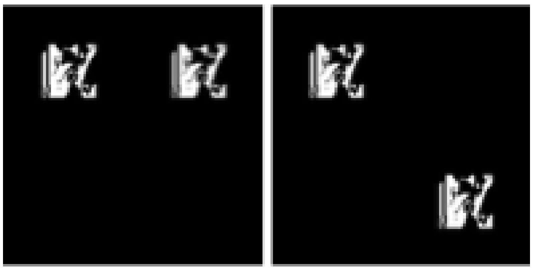


Fig. (4): Application of group2 rules: (a) Image obtained after applying Rule 320P; (b) Image obtained after applying Rule 272P.

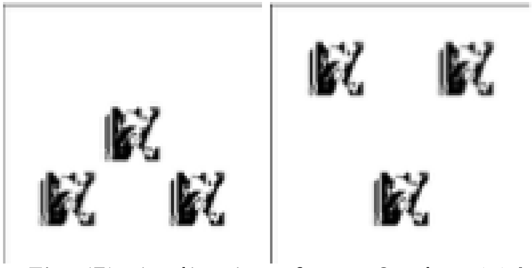


Fig. (5): Application of group3 rules: (a) Image obtained after applying Rule 21P; (b) Image obtained after applying Rule 328P.

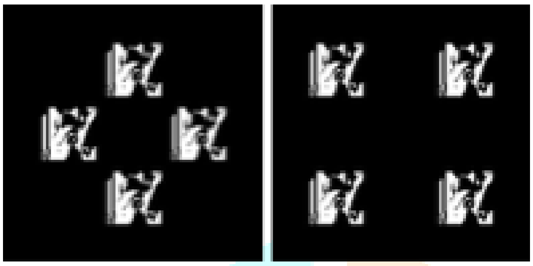


Fig. (6): Application of group4 rules: (a) Image obtained after applying Rule 170P; (b) Image obtained after applying Rule 340P.

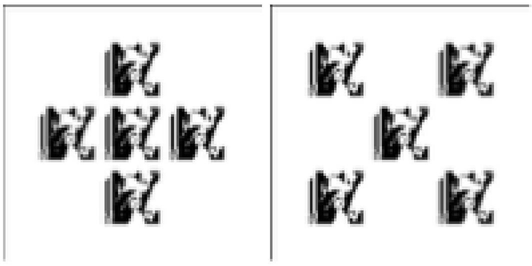


Fig. (7): Application of group5 rules: (a) Image obtained after applying Rule 171P; (b) Image obtained after applying Rule 341P.

Fig. (8): Application of group6 rules: (a) Image obtained after applying Rule 374P; (b) Image obtained after applying Rule 469P.

Fig. (9): Application of group7 rules: (a) Image obtained after applying Rule 477P; (b) Image obtained after applying Rule 475P.

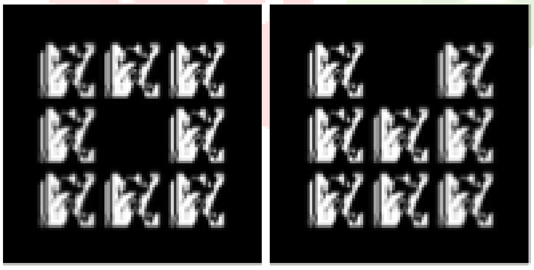


Fig. (10): Application of group8 rules: (a) Image obtained after applying Rule 510P; (b) Image obtained after applying Rule 383P.

Fig.(11): Application of group9 rule: Image obtained after applying Rule 511P

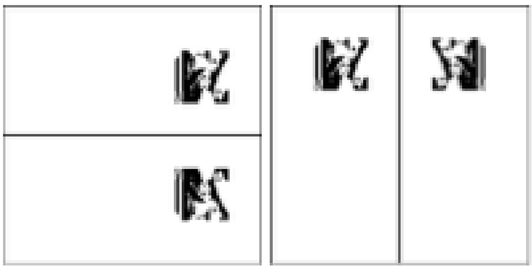


Fig. (12): Reflection of image along x-axis and y-axis: (a) Image obtained after applying Rule 136N; (b) Image obtained after applying Rule 34N.

Fig. (13): Noise cleaning: (a) Original image of Lena corrupted by impulse noise; (b) Noise reduced image obtained after applying Rule 480P (hybrid).

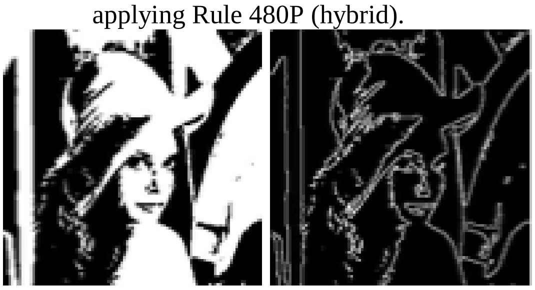


Fig. (14): Edge detection: (a) Original image of Lena; (b) Edge Image obtained after applying Rule 192P

Thinning; The next application of the CA we show is thinning of black regions and so the rules were triggered by black pixels. Thinning is a fundamental preprocessing step in many image processing and pattern recognition algorithms [19, 20]. When an image consists of strokes or curves of varying thickness, it's usually desirable to reduce them to thin representations, which are easier to process in later stages. In such application, the given image is partitioned into four regions were each region is applied a different rule [15]. Thus, we have tested all the rules of group4, where each rule is made up of four rules. All the rules have been tested with Moore neighorhood under periodic boundary condition. The rules which show the characteristics of thinning are listed in the Table 2 and one of such result is shown in Figure 15.

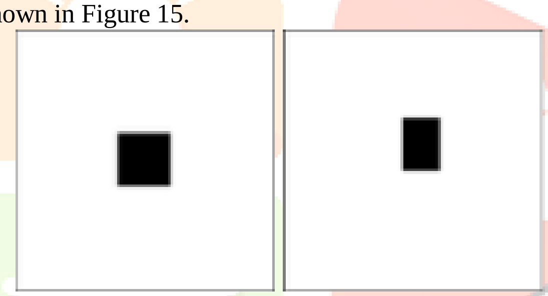


Fig. (15): Thinning of black regions: (a) Original image (b) Thinned image obtained after applying Rule 195P, 15 times

Thinning Rules
195, 196, 198, 201, 204, 209, 210, 212, 216, 225, 226, 228, 232, 240, 330, 329, 326, 325, 323, 332, 344, 340, 338, 337, 387, 368, 360, 356, 354, 353, 389, 390, 393, 394, 396, 401, 402, 408, 432, 424, 420, 418, 417, 464, 456,, 452, 450, 449, 480.

Table (2): rules which show the characteristics of thinning

V. CONCLUSIONS AND FUTURE WORK

In this paper, several experiments are successfully carried out to perform digital image processing tasks such as translation, pattern generations, rotation, noise filtering, edge detection, and thinning of black regions. Uniform as well as hybrid CA rules with periodic and null boundary condition are constructed for perform these image-processing tasks. The time taken to process any image is the order of nanoseconds or microseconds respectively, which will be much faster compared to the other image processing operations.

If the proposed techniques will be interfaced with the programmable device which will be provide the necessary transformations and processing by means of our algorithms and logical programming, novel improvements in the field of digital image processing can be expected. The proposed techniques can be extended to games and animation as the animations are produced by moving the camera or the objects in a scene along animation paths. Although only some important fundamental image transformations are being reported for binary images, we feel that the work can be extended further for any complex image transformations.

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