Designing Efficient Configurable QCA Nano Circuit for Morphological Operations in Image Processing

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Abstract. Morphological operations like erosion and dilation are important operations in various video and image processing applications. This research presents a configurable Quantum-dot Cellular Automata (QCA) nano circuit for morphological applications in image processing. QCA is a field-coupled emerging nano-technology which can be applied in various image processing operations. The implemented QCA design utilizes two cascaded 5-input majority voters where dilation and erosion can be performed with the help of a control line. The proposed design is compared with the previous results which demonstrate substantial improvement in terms of area, delay and cell count.

1. Introduction

The size of transistor is scaling down towards nanometre scale to improve the performance. But, due to physical limitations of CMOS technology, further scale down is facing several problems such as power consumption, electro-migration failures, interconnectivity, lithography problems etc. [1]. Therefore, immense research is going on to find a replacement of current Complementary Metal Oxide Semiconductor (CMOS) technology. Several emerging technologies such as Carbon Nanotubes, Silicon Nanowires, Quantum-dot Cellular Automata, Single-Electron Transistors are emerging as a possible replacement of current CMOS. The Quantum-dot Cellular Automata (QCA) promises higher circuit densities, faster speed, low power consumption over the traditional CMOS technology [2]. The integration densities of QCA technology can touch 1012 cells/cm² and the circuit switching frequency can be close to terahertz [3]. QCA is a field-coupled nano technology where information travels with the help of local interaction between the electrons. Thus, QCA is considered as one of the most propitious nanoelectronic technologies [2,4].

Now-a-days, the most important requirement of any computational system is processing speed and low power consumption. Image processing is a very challenging domain in very-large-scale integration (VLSI) technology due to its huge requirement in computational power. Till date, CMOS based VLSI technology is extensively used to improve the quality of image processing systems. In this regard, several implementations are reported such as nonlinear filters, mathematical morphological operations, multi-functional applications etc.

The complete paper is ordered in the following way: an ephemeral discussion of morphological operations in image processing is presented in section 2. Section 3 will instigate some of the
basics of QCA. The proposed designs are discussed in section 5 followed by conclusion in section 6.

2. Basics of Morphological Operation in Image Processing
Morphological operations act as a tool to extract image components that are useful for further representation and description of the image region. Here, non-linear operations are performed related to the shape or morphology of the image. It does not concern about exact pixel values, but concern about the relative ordering of pixel values. Some of these operations are - Erosion, Dilation, Opening, Closing etc. Erosion and Dilation are the basic operations in morphological image processing. The basic morphological operations are well suited for binary images with only white and black pixels. The inputs of these morphological operations are - the binary image and the binary structuring element. The background and foreground regions are assumed as white and black pixels respectively. The basic morphological operations (erosion and dilation) can be performed on the binary image with the help of a binary structuring element. The structuring element is superimposed over the input image to coincide the origin of the structuring element with the input image.

2.1. Erosion on binary image
In erosion, there are two inputs, the first input is the image that is going to be eroded and another one is the structuring element of known origin, using which erosion is applied to the input image and an eroded image is produced as output. The origin of structuring element visit every pixel of the input image. If the structuring element is totally contained in input image then that location is marked in the processed image. It can be mathematically defined as
\[ I \ominus S = \{(i,j) : S(i,j) \subseteq I\} \]
Here S is the $3 \times 3$ structuring element, I is the input image and $\ominus$ is the erosion operator. The above equation suggests that S is translated by (i, j) and whether that translated S is contained in I (Figure 1).

![Figure 1. (a) Input Image (I) (b) Structuring Element (S) (c) Eroded image](image)

2.2. Dilation on Binary image
In dilation, there are also two inputs, first one is the image that is going to be dilated and another one is the reflected structuring element about its origin. In dilation, as in erosion, the origin of reflected structuring element visit every pixel of the input image and if at that position reflected structuring element is partially contained in input image then that location is marked

![Figure 2. (a) Input Image (I) (b) Structuring Element (S) (c) Dilated image](image)
in the processed image. The mathematical representation of dilation is:
\[ I \oplus S = \{(i, j) : (\tilde{S})_{\tilde{i}, \tilde{j}} \cap I \neq \emptyset\} \]

Here S is a 3x3 structuring element, I is the input image, \( \oplus \) is the dilation operator and \( \tilde{S} \) is the reflection of S about its origin (Figure 2).

### 3. Basics of Quantum-dot Cellular Automata

A QCA cell has four quantum dots with two free electrons. Based on their position, binary logic 0 and logic 1 can be performed. A 3-input majority voter is used as logic gates which can be represented as \( M(A, B, C) = AB + BC + CA \) (Figure 3). By applying fixed polarization at one of the input cells, it can operate as an AND or OR gate. NOT gate can be implemented using two different ways which is shown in Figure 3. Moreover, to increase the programmability feature of the voter, 5-input majority voter is extensively utilized nowadays [5]. The logic function of 5-input majority voter is: \( \text{Maj}(A, B, C, D, E) = ABC + ABD + ABE + ACD + ACE + ADE + BCD + BCE + BDE + CDE \). In this work, we have used 5-input majority voter which is proposed in [5], to implement our designs. QCA clocking has four periodic phases with a \( \Pi/2 \) phase difference between contiguous phases (Figure 4). The four different phases are: switch, hold, release, relax.

### 4. Related Work

The design architecture and fault detection techniques are extensively investigated in QCA [6–8]. However, QCA based designs for image processing applications are not studied in great detail. Few interesting QCA based image processing attempts are discussed in [3, 9, 10]. Image thresholding using QCA is attempted in [9]. In [10], two separate designs for morphological erosion and dilation are proposed. A configurable design for morphological erosion and dilation operation is first attempted in [3] but the design covers huge area, consume more cells and also clock with respect to the design proposed in this work.

### 5. Proposed QCA Designs

#### 5.1. Proposed Non-Configurable Design

A 3x3 structuring element is considered to perform the proposed erosion and dilation operation. First, the structuring element is placed on the input image. For erosion, structuring element should be contained in the input image and for dilation, it should be partially contained. Then, all five-pixel value of the binary image that falls under the marked pixels of 3x3 structuring element is extracted. If all the black pixels of the structuring element coincide with black pixels on the input image, record black the pixel of the output image that corresponds to the
structuring element. If we take AND operation of these pixels then the resultant image will be the eroded image of the input image. Similarly, if we take OR operation of these pixels then the resultant image will be the dilated image of the input image. These two operations can be implemented in hardware as shown in Figure 5. The proposed design consists of two cascaded 5-input majority gates where controlling $l_1, l_2, l_3$ and $l_4$ erosion and dilation can be performed. If $l_1 = l_2 = l_3 = l_4 = -1$ then it performs erosion and if $l_1 = l_2 = l_3 = l_4 = 1$ then it will perform dilation. A comparison between the previous attempt and the proposed work is presented in Table 1 which signifies the superiority of the proposed design.

Figure 5. QCA layout and logical diagram of proposed non-configurable design

Table 1. Comparison of proposed non-configurable design with Mardiris non-configurable design

| Design                  | Cell Count | Clock Cycle | Area ($\mu m^2$) |
|-------------------------|------------|-------------|------------------|
| Mardiris design [10]    | 35         | 3           | 0.043            |
| Proposed design         | 35         | 2           | 0.030            |
| Improvement %            |            |             | 33.33 30.23      |

Figure 6. QCA layout and logical diagram of proposed configurable design

5.2. Proposed Configurable Design For Erosion and Dilation
As it is discussed in the previous section, erosion and dilation can be done using AND and OR gates, a new configurable design for both erosion and dilation is proposed as shown in Figure 6. The design consists of six inputs (A, B, C, D, E and l) and one output (Out). If $l = 1$ then the design performs dilation otherwise it performs erosion operation. The simulation outcomes are displayed in figure 7 and 8. In the Figure 7, the input $l$ is fixed at polarization $P = -1$ whereas in Figure 8, the input $l$ is fixed at polarization $P = 1$. A detailed comparison between previous design and the proposed design is shown in Table 2. The proposed configurable design of erosion and dilation is more area efficient, cost-effective as well as faster than the previous design.
5.3. Simulation Parameters

QCADesigner (Version 2.0.3) [11] coherence vector simulation engine is utilized to substantiate the proposed designs using all the default parameters.

6. Conclusion

In this work, a novel configurable QCA design is discussed for the implementation of erosion and dilation operations for binary images. The configurable QCA design utilized two cascaded 5-input majority voter. The simulation outcomes substantiate the correct operation of the proposed design. The proposed design is more area efficient (11.76%), cost-effective (25%) as well as faster (40%) than the previous design.

Table 2. Comparison of Proposed Configurable design with Mardiris Configurable design

| Design          | Cell Count | Clock Cycle | Area ($\mu$m$^2$) |
|-----------------|------------|-------------|-------------------|
| Mardiris design [3] | 51         | 4           | 0.05              |
| Proposed design  | 45         | 3           | 0.03              |
| Improvement %    | 11.76      | 25          | 40                |