The Development of a Preprocessing Circuit Using Clocked CMOS Neuron Inverters for a Retinal Prosthesis System

Kei Eguchi^{a,*}, Ponglert Rattanachinalai^a, Kanji Abe^a, Yujiro Harada^b, Kuniaki Fujimoto^b

^aDepartment of Information Electronics,
Fukuoka Institute of Technology,

3-30-1, Wajiro-Higashi, Higashi-ku, Fukuoka 811-0295, Japan

^bDepartment of Electronics and Intelligent Systems Engineering,
Tokai University

9-1-1, Toroku, Higashi-ku, Kumamoto 862-8652, Japan

*Corresponding Author: eguti@fit.ac.jp

Abstract

In implantable electronic medical devices, low power consumption and small size are important requirements to design efficient implantable circuits. As a preprocessing circuit of the retinal prosthesis system, this paper presents two types of image processing circuits: a CMOS median filter and a CMOS binarizing circuit. Owing to the CMOS circuit design utilizing clocked neuron CMOS inverters, the proposed circuits can achieve median filtering and binarizing of the captured image without arithmetic logic circuits. Furthermore, the through-current of neuron CMOS inverters can be suppressed by adjusting the duty cycle of clock pulses. Therefore, the proposed circuits achieve not only simple circuit configuration but also low power consumption. The results of the simulation program with integrated circuit emphasis (SPICE) simulation demonstrate the effectiveness of the proposed circuits.

Keywords: Median filter circuits, Image binarization, Image resizing, Neuron MOSFETs, Image processing, Implantable electronics.

1. Introduction

In the field of biomedical engineering, the demand of implantable electronic medical devices is growing rapidly. Among others, the development of a retinal prosthesis system⁽¹⁻³⁾ is one of the most challenging issues to support partial or total blind patients. In the retinal prosthesis system, an image data captured by an external camera is transmitted

to an IC chip implanted near retina by wireless^(2, 3). Hence, the retinal prosthesis system consists of a camera, signal-processing units, a wireless transmitter & receiver, and an implanted stimulator IC chip. However, the existing retinal prosthesis system is bulky and not power-efficient. To develop an efficient retinal prosthesis system with small size and low power consumption, firstly, we focused on the preprocessing circuit to perform median filtering, resizing, and binarizing of the input image.

In previous studies, many types of the preprocessing circuits have been proposed. For example, Kalali et al. implemented an adaptive median filter into a Field Programmable Gate Array (FPGA) chip⁽⁴⁾. Due to the low complexity 2D adaptive median filter algorithm, low power consumption can be realized by Kalali's circuit. In this way, the efficient preprocessing circuit can be realized easily by utilizing embedded systems such as FPGA, Intel Edison, Aduino, and so on. However, the hardware approach based on the embedded system is too bulky for the retinal prosthesis system. Different from these approaches based on embedded systems, Lee et al. proposed a bit-level scalable median filter⁽⁵⁾. The bit-level scalable median filter is suitable for IC implementation, because it can be designed by CMOS technology. Following this, Yamasaki et al. suggested a high speed median filter using floating-gate-MOS-based low-power majority voting circuits⁽⁶⁾. Due to the floating gate MOS technology, the median filter proposed by Yamasaki et al. can achieve not only low power consumption but also high speed operation. The floating gate MOSFET is referred to as a neuron MOSFET⁽⁷⁻¹⁰⁾. It is

known that the floating gate MOS technology can achieve high-speed operation, small size, and low power consumption⁽⁶⁻¹⁰⁾. However, in order to realize more efficient implantable circuit, there is still room for improvement in the point of power consumption.

In this paper, we propose a novel preprocessing circuits using clocked CMOS neuron inverters: CMOS median filter and CMOS binarizing circuit. Owing to the CMOS circuit design utilizing clocked neuron CMOS inverters, the proposed circuits can achieve median filtering and binarizing of the captured image without arithmetic logic circuits, such as adder, subtractor, multiplier, and divider. Furthermore, the through-current of neuron CMOS inverters can be suppressed by adjusting the duty cycle of clock pulses. Therefore, the proposed circuits achieve not only simple circuit configuration but also low power consumption. To clarify the characteristics of the proposed circuits, SPICE (simulation program with integrated circuit emphasis) simulations are performed.

The rest of this paper is organized as follows. In section 2, the proposed CMOS median filter is described. Next, in section 3, the proposed binarizing circuit is presented. Simulation results are shown in section 5. Finally, conclusion and future work are drawn in section 6.

2. CMOS Median Filter

2.1 Operation Principle

The operation principle of the proposed median filter is based on the binary search algorithm. To obtain the k -th ($k=0, \dots, N-1$) bit of the median value $M_i[k]$ ($i=1, \dots, m \times n$) from the input image of $m \times n$ pixels, the following operation is performed:

$$M_i[k] = \begin{cases} 1, & \text{if } \sum_{j \in W} \frac{P_j[k]}{W} > 0.5 \\ 0, & \text{if } \sum_{j \in W} \frac{P_j[k]}{W} \leq 0.5 \end{cases}, \quad (1)$$

where $P_j[k]$ is a value of the j -th pixel and W is the window size. According to the median value $M_i[k]$, the value of the i -th pixel $P_i[k]$ is changed as follows:

$$\begin{aligned} P_i[k-1] &= \dots = P_i[0] \\ &= \begin{cases} 1, & \text{if } P_i[k] \neq M_i[k] \text{ and } P_i[k] = 1 \\ 0, & \text{if } P_i[k] \neq M_i[k] \text{ and } P_i[k] = 0 \end{cases} \end{aligned} \quad (2)$$

By iterating the operation of (1) and (2) from $k=N-1$ to 0, the

median value of P_i is derived.

To help readers' understanding, an example of the median detection is demonstrated in Table 1, where the window size $W=5$ and the bit-length $N=4$. First, in the case of $k=3$, the majority group is $P_1[3]$, $P_3[3]$, and $P_4[3]$. Therefore, we have $M_i[3]=1$, because the majority is "1". On the other hand, the remaining bits of P_2 , and P_5 are all changed to "0". Next, in the case of $k=2$, the majority group is $P_1[2]$, $P_2[2]$, $P_3[2]$, and $P_5[2]$. Therefore, we have $M_i[2]=0$, because the majority is "0". On the other hand, the remaining bits of P_4 are all changed to "1". In the same way, the median value $M_i[1]$ and $M_i[0]$ are obtained by iterating these processes.

Table 1. An example of the median detection.

($W=5$)	$k=3$ (MSB)	$k=2$	$k=1$	$k=0$ (LSB)
$P_1=\{1,0,0,1\}$	$\{1,0,0,1\}$ (Major)	$\{1,0,0,1\}$ (Major)	$\{1,0,0,1\}$ (Major)	$\{1,0,0,1\}$ (Major)
$P_2=\{0,1,1,1\}$	$\{0,0,0,0\}$ (Minor)	$\{0,0,0,0\}$ (Major)	$\{0,0,0,0\}$ (Major)	$\{0,0,0,0\}$ (Minor)
$P_3=\{1,0,1,0\}$	$\{1,0,1,0\}$ (Major)	$\{1,0,1,0\}$ (Major)	$\{1,0,1,1\}$ (Minor)	$\{1,0,1,1\}$ (Major)
$P_4=\{1,1,0,0\}$	$\{1,1,0,0\}$ (Major)	$\{1,1,1,1\}$ (Minor)	$\{1,1,1,1\}$ (Minor)	$\{1,1,1,1\}$ (Major)
$P_5=\{0,1,0,0\}$	$\{0,0,0,0\}$ (Minor)	$\{0,0,0,0\}$ (Major)	$\{0,0,0,0\}$ (Major)	$\{0,0,0,0\}$ (Minor)
Median value $M_{i,j}[k]$	1	0	0	1

2.2 Circuit Configuration

Figure 2 illustrates the block diagram of the proposed CMOS median filter. As you can see from figure 2, the proposed median filter consists of bit-comparators (BCs) and majority circuits (MCs). In figure 2, the median detection is performed by a bit-comparison-based technique in order to realize small hardware cost.

Figure 3 illustrates the logic circuit (LC) in the bit-comparator. The logic circuit of figure 3 is designed to realize the following bit-comparison:

$$L_i[k] = S0_i[k] \cdot S1_i[k] + P_i[k] \cdot \overline{S1_i[k]}, \quad (3)$$

where

$$\begin{aligned} S0_i[k+1] &= S0_i[k] \cdot S1_i[k] \\ &\quad + \overline{M_i[k]} \cdot \overline{S1_i[k]} \cdot P_i[k] \end{aligned} \quad (4)$$

$$\text{and } S1_i[k+1] = M_i[k] \oplus P_i[k] + S1_i[k]. \quad (5)$$

In (3)-(5), $M_i[k]$ is the k -th bit of the median output and $L_i[k]$ is the k -th bit of the BC output.

Fig. 2. Block diagram of CMOS median filter.

Fig. 3. Block diagram of a logic circuit.

The majority of $L_i[k]$ is detected in the majority circuit (MC). In the proposed median filter, the majority circuit is designed by using clocked neuron CMOS inverters. Figure 4 illustrates the proposed majority circuit using a clocked neuron CMOS inverter, where C_p denotes the parasitic capacitance. When the clock Φ is in a high level, the clocked neuron CMOS inverter behaves as a traditional neuron CMOS inverter⁽⁸⁻¹⁰⁾. In this timing, the floating gate voltage $V_{Fi}[k]$ of the clocked neuron inverter is given by

$$V_{Fi}[k] = \frac{\sum_{j \in W} L_j[k] C_u + V_{dd} C_{FN}}{W C_u + C_{FP} + C_{FN}}, \quad (6)$$

where C_u is a unit capacitance between an input terminal and the floating gate, C_{FN} is a capacitance between the floating gate and N -type region, and C_{FP} is a capacitance between the floating gate and P -type region. In the proposed median filter, the unit capacitance C_u is designed to satisfy the following conditions:

$$C_u \gg C_{FN} \quad \text{and} \quad C_{FP} = C_{FN}. \quad (7)$$

From (7), the floating gate voltage V_{Fi} can be rewritten as

$$V_{Fi}[k] \cong \sum_{j \in W} \frac{L_j[k]}{W}, \quad (8)$$

where

$$\sum_{j \in W} L_j[k] \in \{0, V_{dd}, 2V_{dd}, \dots, WV_{dd}\}. \quad (9)$$

From (8) and (9), we have

$$M_i[k] = \begin{cases} V_{dd}, & \text{if } \sum_{j \in W} L_j[k] \leq \frac{WV_{dd}}{2} \\ 0, & \text{if } \sum_{j \in W} L_j[k] > \frac{WV_{dd}}{2} \end{cases}. \quad (10)$$

As you can see from (10), the clocked neuron inverter behaves as a majority circuit when the clock Φ is in a high level. On the other hand, the clocked neuron inverter becomes high-impedance when the clock Φ is in a low level. In this timing, the output voltage is held in C_p . In other words, the proposed majority circuit behaves like a sample-and-hold circuit. Therefore, by adjusting the duty cycle of the clock pulse, the proposed median filter can reduce power consumption, because the through-current of the neuron inverter is suppressed.

Fig. 4. Majority circuit using a locked neuron CMOS inverter.

3. Binarizing Circuit

3.1 Operation Principle

After the median filtering, the input image is converted to a binary image and is resized to the image of $m' \times n'$ pixels. To obtain the pixel value of the resized image, B_i ($i=1, \dots, m' \times n'$), from the input image of $m \times n$ pixels, the following operation is performed:

$$B_i = \begin{cases} 1, & \text{if } \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N P_j[N-l] \cdot 2^{N-l}}{\sum_{j \in W' l=1}^N \sum_{l=1}^N 2^{N-l}} > 0.5 \\ 0, & \text{if } \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N P_j[N-l] \cdot 2^{N-l}}{\sum_{j \in W' l=1}^N \sum_{l=1}^N 2^{N-l}} \leq 0.5 \end{cases}, \quad (11)$$

where W' is the window size to resize the input image. In other words, the resized image satisfies the following conditions:

$$m' = \frac{m}{W'} \quad \text{and} \quad n' = \frac{n}{W'}. \quad (12)$$

Fig. 5. Clocked neuron CMOS inverter.

3.2 Circuit Configuration

To achieve small power consumption and small hardware cost, clocked neuron MOSFET's are employed in

the design of the proposed binarizing circuit. Figure 5 illustrates the proposed binarizing circuit using a clocked neuron CMOS inverter. In the proposed binarizing circuit, the floating gate capacitance is designed as $2^{N-1-k} \times C_u$ for $P_i[k]$. Owing to the binary-weighted floating capacitances, the proposed binarizing circuit requires no arithmetic logic circuit such as adder, multiplier, divider, and so on. Therefore, the proposed circuit can achieve simple circuit configuration.

In figure 5, the floating gate voltage V_{FBi} of the clocked neuron inverter is given by

$$V_{FBi} = \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N C_u P_j[N-l] \cdot 2^{N-l} + V_{dd} C_{FN}}{\sum_{j \in W' l=1}^N \sum_{l=1}^N 2^{N-l} C_u + C_{FP} + C_{FN}}, \quad (13)$$

where the unit capacitance C_u satisfies the condition of (7).

From (7) and (13), we get

$$V_{FBi} = \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N P_j[N-l] \cdot 2^{N-l}}{\sum_{l=1}^N 2^{N-l} W'}, \quad (14)$$

where

$$P_j[k] \in \{0, V_{dd}\}. \quad (15)$$

From (14) and (15), we have the pixel value of the resized image as follows:

$$B_i = \begin{cases} 0, & \text{if } \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N P_j[N-l] \cdot 2^{N-l}}{\sum_{l=1}^N 2^{N-l} W'} \leq \frac{V_{dd}}{2} \\ V_{dd}, & \text{if } \frac{\sum_{j \in W' l=1}^N \sum_{l=1}^N P_j[N-l] \cdot 2^{N-l}}{\sum_{l=1}^N 2^{N-l} W'} > \frac{V_{dd}}{2} \end{cases} \quad (16)$$

As you can see from (16), in spite of a simple circuitry, the proposed circuit can achieve not only binarization but also resizing. Furthermore, owing to the clocked neuron inverter, the proposed circuit can reduce power consumption by adjusting the duty cycle of the clock pulse.

4. Simulation

To clarify the characteristics of the proposed circuits, SPICE simulations are performed by assuming 0.35μm CMOS process.

4.1 CMOS Median Filter

As an example of the proposed median filter, the 3-bits/3-inputs proposed circuit was designed. Figure 6 demonstrates the simulated output of the proposed median filter, where the supply voltage is 1.8V and the duty cycle is 0.5. In figure 6, the input voltages, P_1 , P_2 , and P_3 , are as shown in Table 2. As you can see from figure 6 and Table 2, the proposed median filter can derive the median value M_i from P_1 , P_2 , and P_3 . Figure 7 shows the power consumption of the proposed median filter as a function of the duty cycle. In figure 7, the blue-line shows the power consumption of the proposed median filter, the orange-line shows the power consumption of the conventional median filter using floating-gate-MOS-based low-power majority voting circuits ⁽⁶⁾, and the grey line shows the conventional median filter using CMOS majority circuits ⁽⁵⁾ shown in figure 8. As figure 7 shows, the proposed median filter can reduce the power consumption by controlling the duty cycle. Concretely, the proposed median filter reduced power consumption more than 37% from the conventional median filter ⁽⁶⁾ when the duty cycle is 0.5. Needless to say, the setting of duty cycle depends on the response speed of CMOS transistors.

Fig. 6. Simulated output of the proposed median filter.

4.2 Binarizing Circuit

As an example of the proposed binarizing circuit using a clocked neuron CMOS inverter, the 4-bits/4-inputs proposed circuit was designed. Figure 9 demonstrates the simulated output of the proposed binarizing circuit, where the supply voltage is 1.8V and the duty cycle is 0.5. In figure 9, the input voltages, P_1 , P_2 , P_3 and P_4 , are as shown in Table 3. As you can see from figure 9 and Table 3, the proposed binarizing circuit can offer the pixel value of the resized image, B_i . Figure 10 shows the power consumption of the

proposed circuit as a function of the duty cycle. In figure 10, the blue-line shows the power consumption of the proposed circuit with a clocked neuron CMOS inverter. On the other hand, the orange-line shows the power consumption of the proposed circuit without a clocked neuron CMOS inverter. As figure 10 shows, the proposed circuit with a clocked neuron CMOS inverter can reduce the power consumption by controlling the duty cycle. Concretely, more than 43% power consumption was reduced when the duty cycle is 0.5.

Table 2. Setting of SPICE simulation.

Time (μs)			
From	0	1.0	2.0
To	1.0	2.0	3.0
Input	Value		
P_1	$\{ V_{dd}, V_{dd}, 0 \}$ (6)	$\{ 0, 0, V_{dd} \}$ (1)	$\{ V_{dd}, V_{dd}, 0 \}$ (6)
P_2	$\{ V_{dd}, 0, V_{dd} \}$ (5)	$\{ 0, V_{dd}, 0 \}$ (2)	$\{ V_{dd}, 0, V_{dd} \}$ (5)
P_3	$\{ 0, V_{dd}, V_{dd} \}$ (3)	$\{ V_{dd}, 0, 0 \}$ (4)	$\{ 0, V_{dd}, V_{dd} \}$ (3)
Output	Value		
M_i	$\{ V_{dd}, 0, V_{dd} \}$ (5)	$\{ 0, V_{dd}, 0 \}$ (2)	$\{ V_{dd}, 0, V_{dd} \}$ (5)

Fig. 7. Simulated power consumption of the median filter.

Fig. 8. Conventional CMOS majority circuit.

Fig. 9. Simulated output of the proposed binarizing circuit with a clocked neuron CMOS inverter.

Table 3. Setting of SPICE simulation.

Time (μs)									
From	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
To	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Input	Value								
P_1	15	7	11	3	13	5	9	1	14
P_2	15	14	7	6	11	10	3	2	13
P_3	15	13	14	12	7	5	6	4	11
P_4	15	11	13	9	14	10	12	8	7
Output	Value								
B_i	V_{dd}	V_{dd}	V_{dd}	0	V_{dd}	0	0	0	V_{dd}

Fig. 10. Simulated power consumption of the binarizing circuit.

5. Conclusions

As a preprocessing circuit of the retinal prosthesis system, this paper has presented two types of image processing circuits: a median filter using clocked neuron

CMOS inverters and a binarizing circuit using a clocked neuron CMOS inverter. The SPICE simulations showed the following results:

1. By using clocked neuron CMOS inverters, the proposed median filter can offer median values without arithmetic logic circuits, such as adder, subtractor, multiplier, and divider.

2. When the duty cycle is 0.5, the proposed median filter can reduce about 37% power consumption from the conventional circuit.

3. By using a clocked neuron CMOS inverter with binary-weighted floating-capacitors, the proposed binarizing circuit can achieve simple circuit configuration. Concretely, the proposed circuit consists of 4 MOS transistors and a neuron CMOS inverter.

4. The proposed binarizing circuit achieve small power consumption. When the duty cycle was 0.5, the proposed circuit reduced about 43% power consumption from the conventional circuit.

From these results, the proposed preprocessing circuits will be able to realize small power consumption. The following topics are left to a future study: 1. Overall design of the retinal prosthesis system using the proposed preprocessing circuits, 2. Hardware implementation of the retinal prosthesis system, and 3. Performance evaluation of the experimental circuit such as circuit size, power consumption, response speed, etc.

References

- (1) Takashi Tokuda, Kohei Hiyama, Shigeki Sawamura, Kiyotaka Sasagawa, Yasuo Terasawa, Kentaro Nishida, Yoshiyuki Kitaguchi, Takashi Fujikado, Yasuo Tano, and Jun Ohta : "CMOS-based multichip networked flexible retinal stimulator designed for image-based retinal prosthesis", IEEE Trans. Electron Devices, Vol. 56, No. 11, pp.2577-2585, 2009
- (2) Hideki Naganuma, Kouji Kiyoyama, and Tetsu Tanaka : "A 37×37 pixels artificial retina chip with edge enhancement function for 3-D stacked fully implantable retinal prosthesis", Proc. of 2012 IEEE Biomedical Circuits and Systems Conference, pp.212-215, 2012
- (3) Chih-Lin Lee and Chih-Cheng Hsieh : "A 0.5 V/1.8 V high dynamic range CMOS imager for artificial retina applications", IEEE Sensors Journal, Vol. 15, No. 12, pp.6833-6838, 2015
- (4) Ercan Kalali and Ilker Hamzaoglu : "A low energy 2D adaptive median filter hardware", Proc. of 2015 Design,

Automation & Test in Europe Conference & Exhibition,
pp. 725-729, 2015

- (5) Chang Long Lee and Chein-Wei Jen : “A bit-level scalable median filter using simple majority circuit”, Proc. of 1989 International Symposium on VLSI Technology, Systems and Applications, pp. 174-177, 1989
- (6) Hideo Yamasaki and Tadashi Shibata : “A high-speed median filter VLSI using floating-gate-MOS-based low-power majority voting circuits”, Proc. of the 31st European Solid-State Circuits Conference, pp.125-128, 2005
- (7) Masaaki Fukuhara and Masahiro Yoshida : “Power consumption of a Hamming distance search CAM using neuron MOS transistors”, Proc. of 2006 IEEE International Symposium on Circuits and Systems, pp. 4345-4348, 2006
- (8) Yujiro Harada, Kuniaki Fujimoto, Mitsutoshi Yahara, and Kei Eguchi : “A study on flash type A/D converter using neuron CMOS inverter”, Advanced Materials Research, Vol. 931-932, pp.915-919, 2014
- (9) Yujiro Harada, Kei Eguchi, and Kuniaki Fujimoto : “A size reduction technique for an A/D converter using neuron CMOS inverters”, Journal of Applied Science and Agriculture, Vol. 9, No. 11, pp.132-137, 2014
- (10) Yujiro Harada, Kuniaki Fujimoto, Masaaki Fukuhara, and Masahiro Yoshida : “A minimum hamming distance search associative memory using neuron CMOS inverters”, IEEJ Trans. Electronics, Information and Systems, Vol. 136, No. 1, pp. 36-42, 2016