Implementation of Cellular Neural Network in 5-Transistor Active Pixel Sensors

Aditya Ramesh
Electrical & Computer Engineering Department
University of Florida
Gainesville, FL
ramesh.aditya@ufl.edu

Dr. Eric M. Schwartz
Electrical & Computer Engineering Department
University of Florida
Gainesville, FL
ems@ufl.edu

***Abstract*— A concept for a CMOS image sensor architecture with real-time parallel analog signal processing is presented in this paper. Cellular Neural Networks (CNN) enables image processing in the analog domain using circuit elements such as capacitors, resistors, and nonlinear voltage-controlled current sources. Utilizing CNN for pre-processing in the analog domain allows for real-time feature extraction, noise removal, or other basic image processing, including edge and corner detection. Implementing CNN on a camera requires modification to the CMOS active pixel sensor architecture.**

Keywords—Cellular Neural Network, CMOS Image Sensors, Active Pixel Sensor, Analog Preprocessing

I. Introduction

As the number of IoT devices and robots with visual sensors grows, the need for low power and fast edge computing also increases [1]. While many approaches include compressing data and dimensionality reduction for the limited hardware resources [2][3], many recent literatures are implementing hardware acceleration solutions to meet the rising amount of data and computational power [1]. One such example is the Cellular Neural Network (CNN) introduced by Leon O. Chua and Lin Yang in 1988 [4]

A. Cellular Neural Networks

The Cellular Neural Network is a large-scale nonlinear analog circuit capable of high-speed parallel and real-time signal processing with applications in image processing [4][5]. It is capable of edge detection, corner detection, noise removal, Boolean logic, contour detection, etc., and its connectivity to the nearest neighbor makes it suitable for VLSI implementation [5][6]. Each cell can be implemented using independent voltage sources, independent current sources, capacitors, resistors, and linear voltage-controlled current sources. The only non-linear element in each cell is a piecewise-linear voltage-controlled current source, which can be implemented with an operational amplifier. Given certain conditions and design of the cellular neural network, a constant steady state output is guaranteed [4].

Each cell in a CNN, denoted as $C(i, j)$ where i represents the row and j represents the column as shown in Figure 1 in [4], contains an *input*, *state*, and *output* denoted by u, x, and y respectively. The node voltage v_{uij} represents the input voltage, v_{xij} represents the state voltage, and v_{yij} represents the state voltage of the cell $C(i, j)$. The voltages v_{uij}, v_{xij}, and v_{yij}, are related by the feedback operator $A(i, j; k, l)$ and the control operator $B(i, j; k, l)$ in the equations given in equation 2 in reference [4]. The circuit diagram for a cellular neural network is shown in Figure 3 of reference [4] and an example of an op amp implementation of a cell can be found in Figure 19 of reference [4]. It is important to note that v_{uij} is a constant voltage and both v_{uij} and v_{xij} must satisfy the following conditions:

$$\left|v_{uij}\right| \leq 1$$
$$\left|v_{xij}(0)\right| \leq 1$$

The three node voltage v_{uij}, v_{xij}, and v_{yij} can be normalized to meet these conditions.

B. Active Pixel Sensor

Active pixel sensors (APS) are used in digital cameras to convert the photo-generated signal to an analog voltage, which is then converted to digital data through an analog-to-digital convertor. CMOS APS are often used due to their lower noise when compared to the passive pixel sensor and lower power when compared to the charge coupled devices (CCD) sensors [7][8][9]. APS are constructed with three transistors, often shorted to 3T APS. Other architectures include four and five transistors to reduce noise and utilize global shuttering, however, these have reduced fill factor resulting in smaller pixel sizes [9]. Smaller pixels have lower dynamic range, lower fill factor, worse low light sensitivity, higher dark signal, and higher non-uniformity [10].

As shown in Fig. 1a, the reset transistor is used to reset the pixel. When reset is off, the photodiode accumulates charge where the voltage can be read by the source follower transistor in the 3T APS, which acts as a non-inverting buffer. This output voltage is then read when the row and column signal is selected [9]. Each pixel is read sequentially in the 3T architecture, resulting in a rolling shutter. Rolling shutter can lead to image distortion when fast moving objects appear in the frame. 4-Transistor (4T) and 5-Transistor (5T) architectures, as shown in Fig 1b and 1c respectively, are used to implement a global shutter and reduce noise [11].

The 4T APS architecture works similarly like 3T but places a transistor with V_{REF} as the gate signal. V_{REF} is a ramp voltage

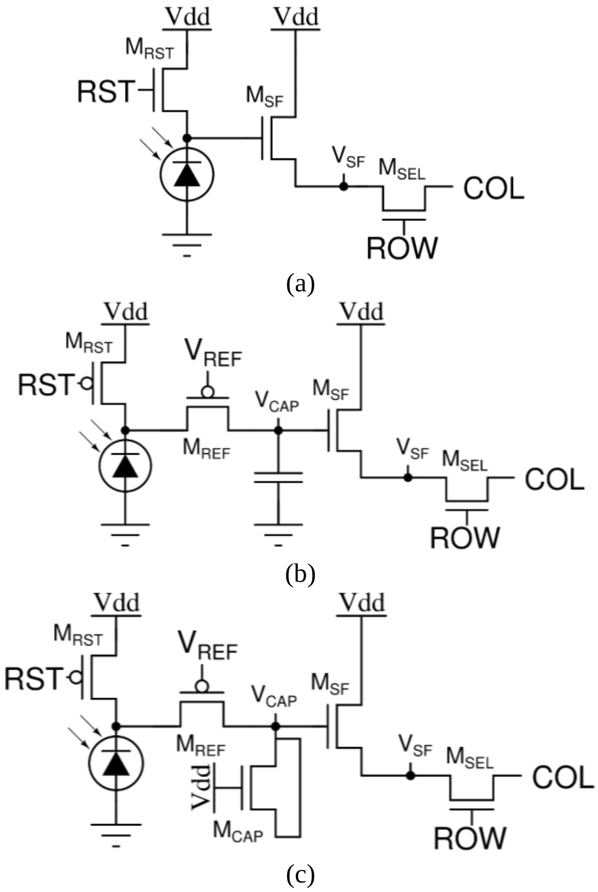

Fig. 1. Architecture of active pixel sensor. a) 3-Transistor. b) 4-Transistor. c) 5-Transistor

and integrates the photodiode's accumulated charge until the transistor is off. It is then stored in a capacitor which acts as memory and is used to reduce thermal noise. This capacitor is replaced with a transistor in 5T APS architecture. The source follower and row select transistor then follows and has the same functionality as the 3T APS.

II. 5T Sensor Architecture with Cellular Neural Network

To enable CNN in the 5T APS architecture, the input voltage of the cell v_{uij} must be constant. The output of the source follower V_{SF} changes as V_{REF} increases. When V_{REF} reaches the voltage required to turn M_{REF} off, V_{SF} reaches a constant voltage. Fig. 2 shows a potential solution to implement the CNN into the 5T architecture. Another transistor M_{EN} is introduced to enable the input into the CNN once V_{SF} reaches its steady state. When M_{EN} is turned on, the CNN is enabled and the output v_{yij} can be read once it reaches steady state. The inputs and outputs of the neighboring cells must also be connected to the CNN. The inputs and outputs of the neighboring cells must also be connected to the CNN. The global shutter effect of the 5T APS ensures that when M_{REF} is off for one pixel, it is off for all pixels. Therefore, v_u and v_y of neighboring cells can be directly connected to input of each cell. v_{yij} can then be read by the row and column select signal.

III. Future Work

Certain factors must be considered when physically implementing CNN in the APS such as maximizing the sensor's fill factor to reduce the non-idealities, including dark current and non-uniformity. Directly implementing the CNN onto the pixel may result in extremely large pixel sizes, essentially reducing the functionality of the camera. Instead, a solution that utilizes vertical layers could be considered to maintain the fill factor. For example, Sony recently developed a 2-layer CMOS APS, separating the photodiodes from the transistor, allowing for optimization of the photodiode and transistor circuit independently [12]. It is also discussed in [13], where a stacked chip is used for computational imaging. A similar approach can be taken where an extra layer is added for the CNN's circuit.

References

[1] A. Bourechak, O. Zedadra, M. N. Kouahla, A. Guerrieri, H. Seridi, and G. Fortino, "At the Confluence of Artificial Intelligence and Edge Computing in IoT-Based Applications: A Review and New Perspectives," Sensors, vol. 23, no. 3, p. 1639, Feb. 2023, doi: 10.3390/s23031639.

[2] F. De Vita, G. Nocera, D. Bruneo, V. Tomaselli, D. Giacalone, and S. K. Das, 'Porting deep neural networks on the edge via dynamic K-means

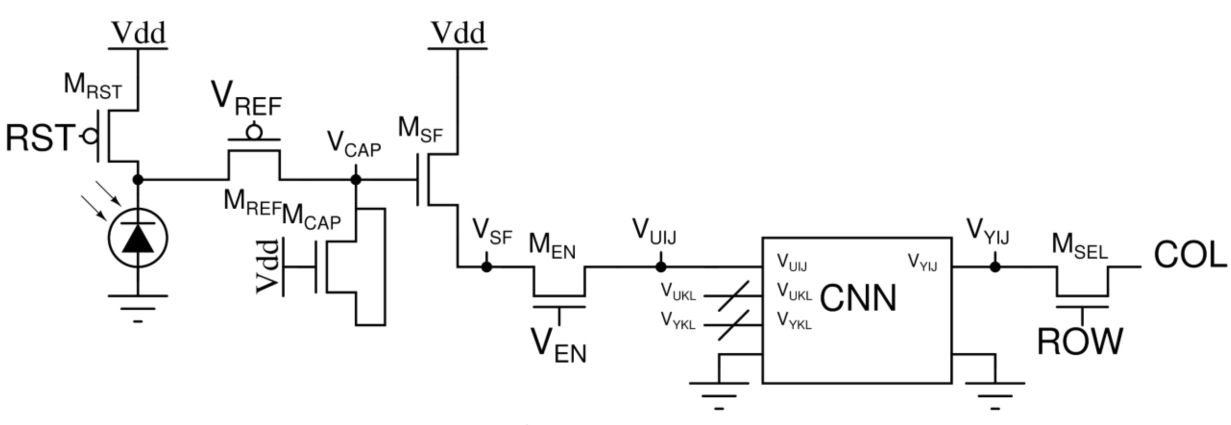

Fig. 2. Architecture of 5-T APS with cellular neural network.

compression: A case study of plant disease detection', Pervasive and Mobile Computing, vol. 75, p. 101437, 2021.
[3] Gupta, N., Khosravy, M., Patel, N. et al. Economic data analytic AI technique on IoT edge devices for health monitoring of agriculture machines. Appl Intell 50, 3990–4016 (2020). https://doi.org/10.1007/s10489-020-01744-x
[4] L. O. Chua and L. Yang, "Cellular neural networks: theory," in IEEE Transactions on Circuits and Systems, vol. 35, no. 10, pp. 1257-1272, Oct. 1988, doi: 10.1109/31.7600.
[5] L. O. Chua and L. Yang, "Cellular neural networks: applications," in IEEE Transactions on Circuits and Systems, vol. 35, no. 10, pp. 1273-1290, Oct. 1988, doi: 10.1109/31.7601.
[6] L. O. Chua and T. Roska, "3," in Cellular Neural Networks and visual computing: Foundations and Applications, Cambridge: Cambridge University Press, 2005.
[7] Kozlowski, L.J. & Luo, J. & Kleinhans, W. & Liu, T.. (1998). Comparison of passive and active pixel schemes for CMOS visible imagers. Proceedings of SPIE - The International Society for Optical Engineering. 3360. 101-110. 10.1117/12.584474.
[8] E. R. Fossum, "CMOS image sensors: electronic camera-on-a-chip," in IEEE Transactions on Electron Devices, vol. 44, no. 10, pp. 1689-1698, Oct. 1997, doi: 10.1109/16.628824.
[9] N. N. Veludandi "CMOS active pixel sensor," M.S. thesis, Electrical Engineering Dept., New Mexico State University, New Mexico, 2006. [Online]. Available: https://wordpress.nmsu.edu/pfurth/files/2015/06/CMOS_ActivePixel_Sensor_Veludandi_2006.pdf
[10] J. Farrell, F. Xiao, and S. Kavusi, "Resolution and light sensitivity tradeoff with pixel size," *Stanford University*, [Online]. Available: https://web.stanford.edu/~jefarrel/Publications/2000s/2006_Farrell_Feng_Kavusi_SPIE06_final.pdf
[11] Che-I Lin, Cheng-Hsiao Lai and Ya-Chin King, "A four transistor CMOS active pixel sensor with high dynamic range operation," Proceedings of 2004 IEEE Asia-Pacific Conference on Advanced System Integrated Circuits, Fukuoka, Japan, 2004, pp. 124-127, doi: 10.1109/APASIC.2004.1349425.
[12] K. Zaitsu et al., "A 2-Layer Transistor Pixel Stacked CMOS Image Sensor with Oxide-Based Full Trench Isolation for Large Full Well Capacity and High Quantum Efficiency," 2022 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits), Honolulu, HI, USA, 2022, pp. 286-287, doi: 10.1109/VLSITechnologyandCir46769.2022.9830372.
[13] Gouveia, L., "Advances on CMOS image sensors," Sensor Review, 36(3), pp. 231-239. 2016, doi:10.1108/SR-11-2015-0189