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Pulse Amplitude Modulation for Electro-optical Spiking Neural Networks

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Abstract—**Spiking neurons represent the most accurate model of the neural cells by using pulses and timing for information processing and adaptation. Visible light communication can be leveraged to establish a wireless link between neurons in spiking networks even when neural areas are in relative motions. Typically, parallel transmission in electro-optical spiking neural networks is performed using wavelength division multiplexing, which is limited by the number of wavelengths used and multiple bandpass optical filters. This paper explores the possibility of using multi-level pulse amplitude modulation (PAM) in multi-input-optical-axons (MIOA) integrated by the parallel neural paths in a spiking neuron network (SNN). To evaluate PAM-MIOA, we implement an electro-optical SNN that controls the force of two anthropomorphic fingers actuated by the shape memory alloy (SMA)-based actuators. The voltage threshold level in PAM is automatically adjusted based on the reference optical power. Results show that the electro-optical SNN is able to hold an object when using PAM-MIOA even with the link misalignment.**

Keywords—Spiking neural networks, visible light communication, Anthropomorphic fingers, optical axon, pulse amplitude modulation.

I. INTRODUCTION

The electronic spiking neurons (SNs) have the main advantage of parallel information processing and transmission as in neural cells, which qualifies them for the hardware implementation of artificial neural areas with real-time operations [1], [2]. When such neural networks are used to control the anthropomorphic hands with neuromorphic sensors, the neurons included by the sensors are at different distances from the main neural unit, which is typically implemented in the robot's body or head. An elegant method to implement communication in these distributed spiking neural networks (SNNs) is based on visible light communications (VLC) for wireless transmission of information between neurons. However, the hand motions determine the variation of the optical signal intensity due to changes in the channel length and alignment. Recently, the optical axons (OAs) have been proposed as a solution to increase the tolerance of electro-optical neural networks to the optical signal fading [3]. These OAs were used to connect the neuromorphic force sensors of two opposing fingers to the main SNN that regulates the fingers' force [4].

Light-emitting diode (LED)-based OAs in humanoid robots are sustained by the limited length of the optical channels within a range of 2 m considering the average height of humans. The neuromorphic sensors used for the implementation of a wide range of senses convert the physical measure into a spiking frequency. For example, a robotic hand controlled by SNN includes three proprioceptive sensors for each finger reaching 16 sensors for a realistic motor-driven hand [5],[6]. This implies that a fully connected hand using VLC will include more than 80 parallel channels only for sensing. The number of channels increases if VLC is also used in actuators in each finger.

Wavelength division multiplexing (WDM) is an option for parallel transmission but is costly and complex due to the requirement of optical bandpass filters. Filterless WDM have been proposed to reduce the high implementation cost [7] - [9]. In [7], M symbols were encoded using 2^n, where n is the number of wavelengths. At the decoder, a photodetector (PD) is used to detect which LEDs are activated based on preset voltage threshold levels. Alternatively, the optical receivers (Rx) responsivity as a function of the wavelength has been used [9]. The combination of responsivity and the LEDs characteristic was used to implement a WDM MIMO system for parallel data transmission [8].

However, the available LEDs have a limited spectrum range that can be used in WDM-MIMO. In this paper, we propose multi-level pulse amplitude modulation (PAM) to implement communication between neurons in SNNs. Note that more spikes can be transmitted simultaneously due to parallel activation of neurons, resulting in higher PAM level. This will introduce non-linearity in the transmitted signal due to the superposition of optical pulses and consequently deteriorate link performance. Considering that the insignificant duration of neuron activation is related to the inter-activation interval and the intrinsic tolerance of SNN to missing or extra spikes, this disadvantage of PAM can have an insignificant effect on SNN activity.

OAs have been used recently to connect neuromorphic force sensors to the main SNN, which controls the contraction

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of SMA actuators. The hand was able to hold an object between the index and thumb despite the relative motion of the transmitter (Tx) and the Rx of OAs. The parallel communication between sensors and the main SNN was implemented using WDM with optical bandpass filters . In the current work, we evaluate for the first time the wireless multi-level PAM VLC in electro-optical SNN, where we show that the robotic hand can hold on to an object when sensors and SMA actuators are connected to the main SNN using single color OAs.

The remainder of the paper is organized as follows: the system structure and the experimental setup are presented in the following two sections. Section IV describes each test scenario and its associated results, and the conclusions of the work are given in the last section.

II. THEORETICAL ANALYSIS

In this work, PAM is used in place of WDM because of the limited spectrum of the LED. We estimate the number of potential levels that can be discriminated in a given voltage interval. The generated voltage at the optical Rx is given by [7]:

$$y(t) = \left(x(t)a_f \otimes h_c(t)\right)\mathcal{R}(\lambda) + n(t), \qquad (1)$$

where $x(t)$ is the reference optical signal for the LED a_f is a multiplication factor specific to the PAM levels, $\otimes$ is the convolution in time domain, $\mathcal{R}$ is the PD responsivity, $h_c(t)$ is the channel gain, and $n(t)$ is the additive white Gaussian noise.he dominant source of noise in the VLC system is the background light-induced shot noise given by [10]:

$$\sigma_{\mathrm{BG}}^2 = 2qB_{\mathrm{ef}}\mathcal{R}I_{\mathrm{bg}}, \qquad (2)$$

where is q is the electron charge, B_{ef} is the bandwidth of the electrical filter at Rx and I_{bg} is the photocurrent induced by the background radiation.

Assuming the PD response and power-current ($P - I$) characteristic of the LED are linear, the number of channels that can be discriminated using PAM is determined by the ratio between the maximum voltage generated by the optical Rx and the noise level. When using PAM VLC between electro-optical spiking neurons, the probability of simultaneous axon activation should also be considered. This probability is reduced because the OAs transmit trigger pulses with the duration limited only by the hardware.

III. SYSTEM STRUCTURE

The proposed system is designed to validate the PAM VLC link between spiking neurons, which includes an electro optical SNN that controls the force of two opposing fingers of an anthropomorphic robotic hand which is shown in Fig. 3. This SNN drives SMA wires that actuate the fingers and receive feedback from neuromorphic sensors, which respond to the force applied to fingertips. As presented in Fig. 4 the SNN is connected to SMA drivers and neuromorphic sensors via VLC using multiple input optical axons (MIOA).

A. Multiple input optical axon

Fig. 1 presents the general structure of the PAM based MIOA. The information from neuromorphic sensors, including a sensing device with an analogue output and a SOMA, are multiplexed in OAs. Note that the SOMA represents the input module of the spiking neurons which detects the activation threshold and signals the neuron activation. MIOA uses a LED for each input and a single optical Rx with its output connected to an analogue-to-digital converter in a microcontroller (µC). Considering LEDs are driven by different currents, the µC can discriminate by the amplitude of the pulses which neuron fires and activate the corresponding synapses (SYNs). The structure presented in Fig. 1 is suitable also for driving multiple actuators.

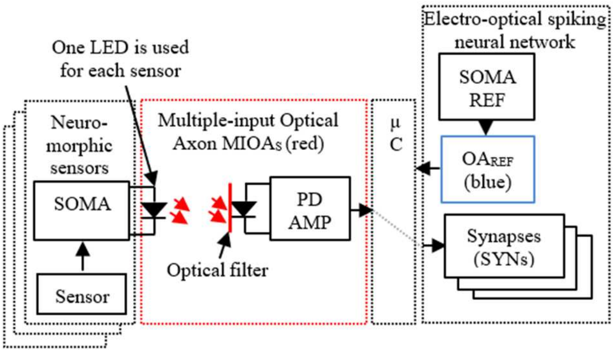


Fig. 1. The structure of the multiple input optical axon that uses multi-level pulse amplitude modulation for multiplexing the inputs received from neuromorphic sensors.

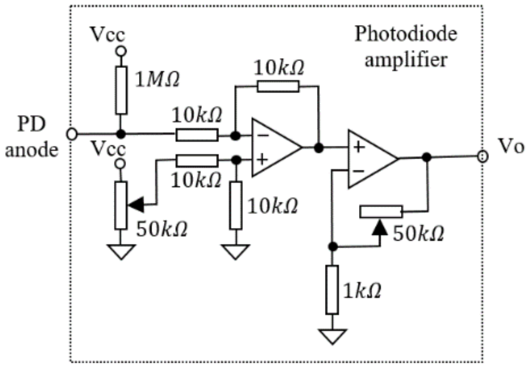


Fig. 2. The schematic of the receiver with PD and amplifier.

For this goal, a similar MIOA receives the inputs from SOMAs of the input neurons and a similar µC activates the corresponding excitatory synapses, which activates the motor neurons that trigger the SMA drivers. The schematics for the SOMA and the synapses are given in our previous work [3], while the schematic of the amplification stage of the optical Rx is presented in Fig. 2.

B. Anthropomorphic hand

The robotic hand includes two fingers with active and blocked junctions as shown in Fig. 3. The finger's flexion can be stopped by the external forces that are perceived by two compression load cells (CLCs) placed on the finger's apex. The CLC and the corresponding SOMA build a neuromorphic sensor, which transmits optical pulses, with variable frequency, to the main SNN via OAs. Similarly, SMA drivers receive optical pulses from SOMAs of the motor neurons, which regulate the actuators' contraction force.

The general structure of the system based on electro-optical SNN for the control of the robotic hand is presented in Fig. 4. The electro-optical SNN uses MIOA with optical channels in the red spectrum to activate SMA drivers and to receive feedback signals from neuromorphic sensors. The drive currents for red LEDs are set to different levels between OAs to implement PAM.

The microcontroller (Infineon XMC4700) reads the amplified pulses generated by LEDs and activates the corresponding synapses based on several voltage threshold levels. To implement OA's tolerance to optical signal fluctuations [3], the initial threshold levels are proportionally modified according to the spike with the maximum amplitude at every 200 ms.

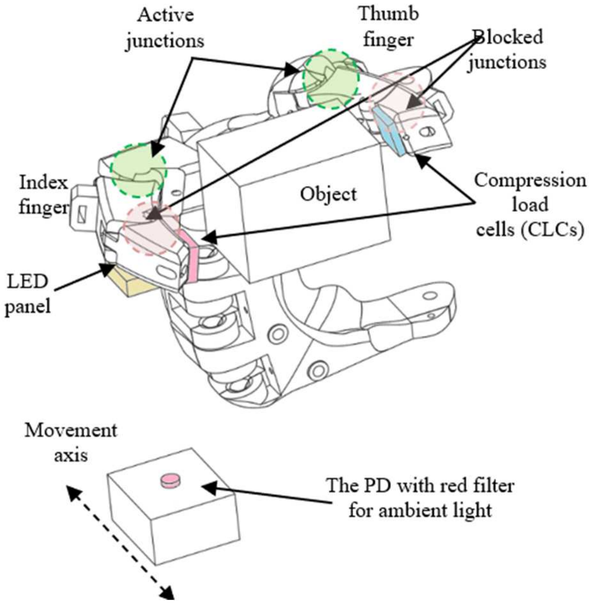


Fig. 3. The structure of the robotic hand with two opposing fingers.

The corresponding LED is connected to a SOMA$_R$ that is activated continuously at 33 Hz, which is four times lower than the firing rate of SOMA$_{EI}$ driving the same LED.

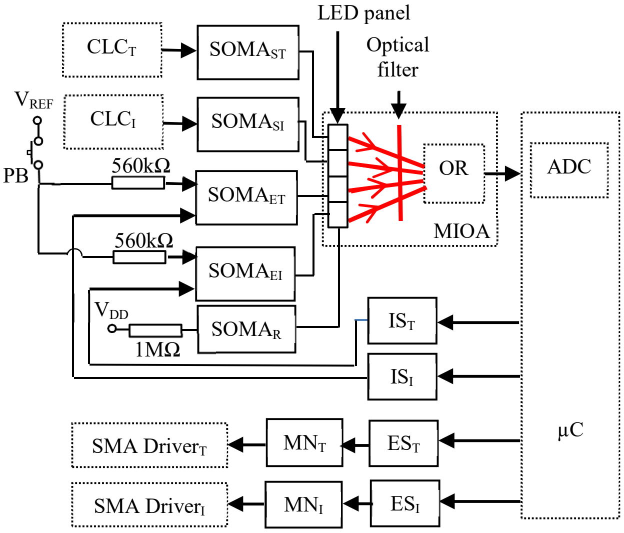


Fig. 4. Electro-optical SNN for the bidirectional control of two fingers; Multiple input OA uses red optical channels of different amplitudes; The LED with the maximum amplitude is taken as the reference; this LED is activated continuously at a low frequency by SOMA$_R$.

When push button is pressed SOMA$_{EI,ET}$ activates the corresponding synapses ES$_{T,I}$ via MIOA and the microcontroller. This determines the contraction of SMA actuators through the SMA drivers, which are driven by motor neurons MN$_{T,I}$. On efferent neural paths, the μC activates the inhibitory synapses IS$_{T,I}$ according to the firing rate of SOMA$_{T,I}$ included by the neuromorphic sensors.

IV. EXPERIMENTAL SETUP

Fig. 5 shows the experimental setup for the evaluation of a robotic arm holding on to an object when Multi-level PAM MIOA is used to connect the SNN with sensors and actuator drivers. The SNN receives information from sensors prior to simultaneously transmitting them to the robotic arm elements. Hence, in a typical application, a single MIOA and microcontroller are used to implement the communication link which is being adopted here to connect sensors and drivers to the SNN. LEDs are mounted on one finger, which is static relative to the ORs while holding an object. All the key system parameters are given in Table I.

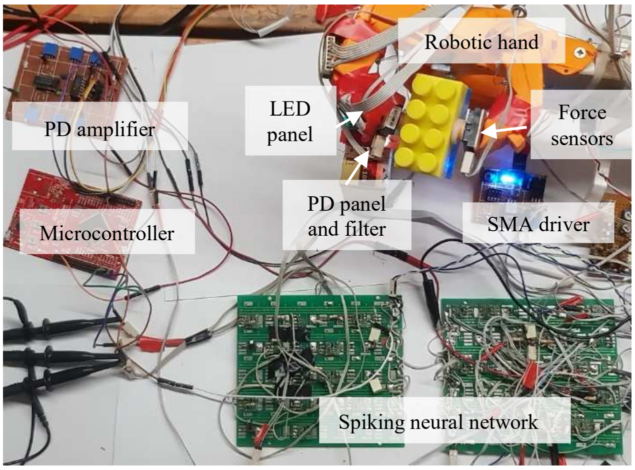


Fig. 5. A photograph of the robotic hand when it holds an object.

For analysis of the system operation, we monitored the activity of motor neurons and the output V_{FS} of CLCs with and without MIOA, as well as for the case with the hardwire connection between SOMA and SYNs.

TABLE I. SYSTEM PARAMETERS

Component	System parameters			
LED CREE XLamp	**Colour**	**Wavelength, λ**		**LED current, I_v**
	Red	640 nm		Variable
	Type	**λ for peak sensitivity**		**Bandwidth, $\lambda_{0.5}$**
PD	BPW20R	920 nm		550 – 1025 nm
Microcontroller	**Type**	**CPU**	**Detection module**	**Sampling Frequency**
	XMC4700	ARM Cortex-M4	ADC	200 kHz
Multi-input Optical axon	**The voltage that power the LEDs:**			
	10 V	8 V	4.7 V	4.0 V
	Initial voltage thresholds for LEDs generated pulses			
	2.1V	1.7V	1.3V	0.9V
Optical filter	**Colour**	**Material**		
	Red	Gel filter film		
Environment	**Temp.**	**Ambiental illuminance**		
	25 ˚C	150 - 180 lux		
SMA actuators Flexinol	**Diameter**	**Pull force**	**Max current**	**Length**
	0.006”	321 g	410 mA	130 cm

Based on mean values and the oscillation amplitude of V_{FS}, we determined the influence of MIOA on the regulatory performance of the SNN.

The first phase of the experiments consisted of evaluating the SNN characteristics when the hand was holding an object between the two fingers without optical connections. In this case, SOMAs of sensors and excitatory neurons were hardwired to the corresponding inhibitory synapses and the excitatory synapses that activate SMA drivers, respectively.

SOMAs were connected to the MIOA that activated the corresponding synapses during the second phase. In this setup, we set the distance d_y between LEDs and optical Rx to 9 cm and performed several measurements when the optical Rx was moved along an axis which is perpendicular to the line-of-sight (LOS) propagation path, see Fig. 3.

V. RESULTS AND DISCUSSIONS

To evaluate the performance of the electro-optical SNN in controlling SMA actuators, we captured the output of CLCs for 10 s using a digital oscilloscope (Keysight Technologies model DSO-X 2004A). The high-resolution acquisition mode was activated on the oscilloscope to reduce the noise on the recorded signals. Fig. 6(a) presents motor neuron output signals when SOMAs and SYNs are connected directly through hardwired axons [11].

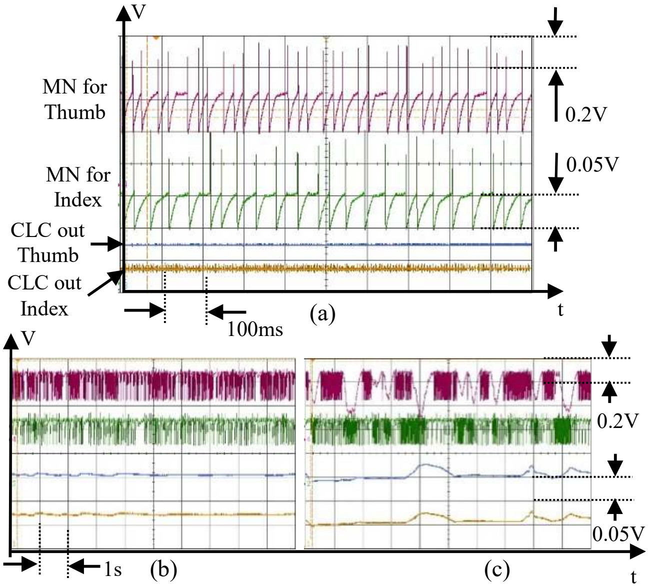
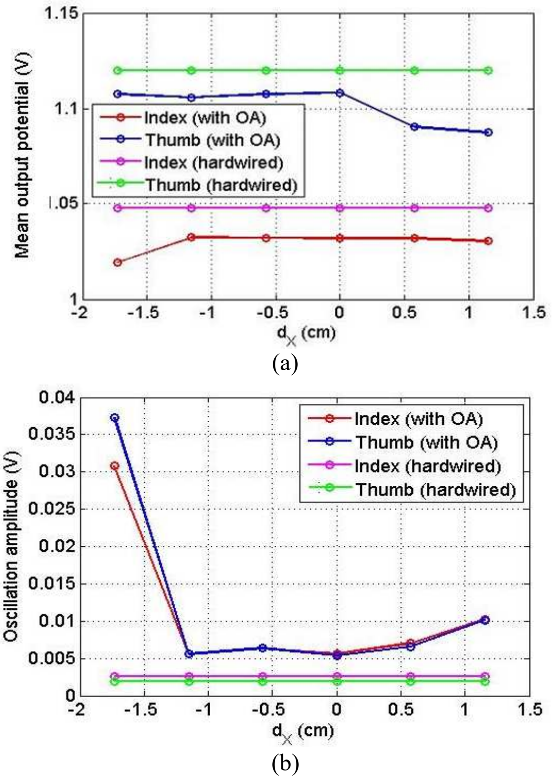


Fig.. 6. The signals on the oscilloscope during holding with: (a) hardwired axons, (b) around LOS with optical axon, and (c) the optical Rx was moved to one side by 1.7 cm.

The magenta and green signals at the SOMA input represent the activity of the motor neurons MN, which drive SMA actuators used for the flexion of the thumb and index fingers. The blue and yellow signals represent the output of the CLCs for both fingers, respectively. Similarly, Figs. 6(b) and (c) show the motor neuron activity and the CLC output during the steady-state for the LOS, respectively, when the OR is moved to the one side.

Comparing the results with hardwired axons, the oscillation amplitude is higher when MIOA is used, and the misalignment of the optical channel makes the oscillation worse. This behaviour can be determined by the adaptive voltage thresholds which are adjusted linearly without taking into account the beam profile of LEDs. Note that the variation of the voltage generated by the sensors is determined by the motor neuron activity, which is significantly affected by the channel misalignment. However, the correlation between the variations of the sensor's output and the neurons' firing rate is a goal of our future research.

However, although the mean of the sensor output changes when MIOA is used, the received signal deviation in the considered range does not affect the hand's ability to hold an object. For the captured signals, we calculated the mean, and maximum variation, which are presented in Fig. 7.



(a)

(b)

Fig. 7. (a) The mean potential generated by the sensors, and (b) the maximum oscillation amplitude during steady-state with MIOA.

VI. CONCLUSIONS

In this work, we investigated the possibility of using PAM MIOA with adaptive threshold levels to connect the neuromorphic sensors and SMA drivers to the main neural control units of robotic hands. MIOA provides the bidirectional communication link between sensors and SNN on afferent paths as well as between SNN and actuator drivers on efferent paths. The SNN performance to regulate the fingers' force was evaluated by determining the mean and oscillation amplitudes of sensors' outputs during the steady-state. The results demonstrated that the influence of the proposed MIOA on the regulatory performance of the SNN depends on the physical displacement of the optical Rx relative to the LED panel. However, this influence did not affect the ability of the robotic arm to hold the object. Although, in this setup, the optical Rx displacement range was low (i.e., $d_x \leq 1.7$cm when $d_y = 9$ cm) for the active optical channels, the results can be improved further by using more sensitive Rxs and high-speed analogue electronics to detect voltage thresholds. Also, the adaptability should be improved by considering the beam profile of LEDs.

The future work includes further investigation of MIOA by increasing the number of channels and improving MIOA tolerance to the optical signal fading.

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