Towards a Neuromorphic Tactile Sensing Glove

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Abstract. This paper presents a prototype of a neuromorphic tactile sensing platform configured as a glove demonstrator. The core of the entire system are the tactile sensing and processing chips, which utilize event-driven approaches, thus, mimicking the power-efficient sensing and processing seen in the human somatosensory system and the brain. The compact glove-integrated platform offers essential signal conditioning, power delivery, and data handling to the neuromorphic chips. Powered and interfaced externally through a singular USB cable, this innovative platform paves the way towards demonstrating human-like high-resolution tactile sensing in future robotic and prosthetic applications.

Keywords: Neuromorphic · Tactile Sensing · Spiking Neural Network

1 Introduction

High-resolution tactile sensors are vital for robotic and prosthetic advancements [1] as they mirror the abilities of the human fingertip. Human skin, which is inherently *multi-modal* and *multi-scale*, encodes tactile data into spatio-temporal spike trains through diverse afferents sensitive to static or dynamic forces [2]. The multi-scale aspect of human touch is evident in the varied afferent densities and receptive field sizes, notably with fingertip afferents around tenfold denser than those in the palm [2].
Mimicking humans, existing "electronic skin" (*e*-skin) systems consist of a network of sensors that measure parameters like static and dynamic forces (normal or multi-axial) and that transmit this information to central processing units to classify or interpret the tactile information. Current e-skin solutions [3,4] convert sensor data into "events" or "spikes" at software level, often relying on overdesigned off-the-shelf readout electronics and performing classification in software offline, missing the opportunity to optimize for the sparse nature of tactile information [5]. Therefore, existing *e*-skin systems stand in stark contrast to the high spatial resolution and power-efficient sensing and processing observed in the human somatosensory system and brain, respectively.
To mimic the rich tactile information sensing by the human fingertips and the

energy-efficient processing by the brain during object manipulation, a prototype neuromorphic tactile sensing platform embedded on a glove demonstrator is proposed. A key innovation is by combining a high-spatial-resolution spike-based tactile sensor readout chip with integrated tactile sensors, and a neuromorphic digital spiking neural network processor. The proposed platform, which provides the necessary signal conditioning, power delivery, and data handling, will then enable real-life and real-time future tactile sensing experiments.
This paper is structured as follows. In Section II, the custom designed neuromorphic chips will be presented in more detail. Section III will describe the design of the glove demonstrator, covering both the hardware implementation as well as the software architecture. In Section IV, the practical challenges of integrating the custom chips in the demonstrator will be described. Section V will conclude the paper.

2 Neuromorphic Chips

2.1 INTUITIVE: A 200μm-Spatial-Resolution Spiking Readout Chip with Integrated Tactile Sensors

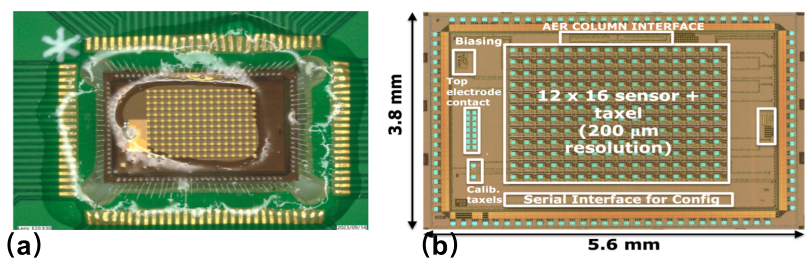

Fig. 1. (a) shows the INTUITIVE chip under microscope, with highlighted epoxy encapsulation and the sensing unit exposed. (b) presents a micrograph of the INTUITIVE chip, with several sub-blocks highlighted, including the 12×16 per-taxel readout and AER interface.

The INTUITIVE chip (as shown in Fig.1(a)(b)) [6] is a 200μm-spatial-resolution tactile sensor readout chip with a 12×16 polyvinylidene flouride (PVDF)-based piezoelectric sensor array and per-taxel sensor-to-spike readout conversion channels. The INTUITVE chip, designed in 0.18μm CMOS technology, consumes only 12.33 nW per-taxel and 75 μW-5 mW for the entire chip, depending on the spike rate. Each of the 192 sensors on the chip are connected to a per-taxel signal conditioning frontend and sensor-to-spike readout channel. The output spikes are then asynchronously encoded and transmitted off-chip using the Address Event Representation (AER) protocol, which is compatible with existing neuromorphic spike-based processors. This integrated event-driven chip-based approach is in contrast to previous software-based sensor-to-spike conversion methods, offering a power-efficient approach in converting *sparse* tactile signals.

2.2 Freya: A Digital Spiking Neural Network Processor Chip with Level-Crossing Converters

Freya is a lightweight digital Spiking Neural Network (SNN) processor based on the design outlined in [7]. It features a 256-neuron, 64k-synapse crossbar neurosynaptic core and is designed for low-power embedded neural network applications. The synaptic weights in the SNN are represented as signed 4-bit numbers. Freya is capable of performing inference using SNN parameters that are provided through the SPI interface.

Due to the limitation of having only 256 neurons with the synaptic weights being signed 4-bit numbers, training a model to be compatible with Freya for processing data from the INTUITIVE chip requires careful consideration. The total number of neurons across all layers of the network may not exceed 256, and additionally, the network must employ quantization techniques to fit into the 4-bit constraint.

3 Platform Design

3.1 Hardware

The system diagram of the proposed e-skin glove demonstrator platform is shown in Fig.2. The system encompasses three core components: the INTUITIVE sensor, the SNN processor Freya, and a Microcontroller Unit (MCU STM32F439IIT6). The INTUITIVE chip outputs sensor-encoding digital spike signals using the Address-Event Representation (AER) protocol [5]. Using the INTUITIVE chip's output spikes, the Freya SNN processor then performs inference tasks using its neuron core and pre-stored SNN network parameters (weights). The MCU orchestrates the system, handling data preprocessing and facilitating communication between the sensor and the SNN processor chip.

As depicted in Fig.2, the entire glove hardware design is split into two distinct parts: one dedicated to the fingers and the other to the wrist, with both parts interconnected through flexible PCB connections. The fingertip PCB, through miniature headers, connects to the INTUITIVE chip (in itself packaged on a similarly-sized PCB) while providing local chip biasing currents and housing the flex cable connectors to the main board. Each flex cable connector relays the per-finger AER signals, and the chip's required voltage references and power supplies. To facilitate easy wearability on the fingers, this design is constrained to a compact size of 2×1 cm^2. Meanwhile, the wrist boards feature a stacked design to achieve a reduced footprint: the upper board houses the MCU, while the lower board houses the Freya chip. The MCU allows the queuing and the preprocessing (*i.e.,* denoising and downsampling) of the digital spike output from the multiple per-finger INTUITIVE chips. Since the MCU should support enough I/O interfaces and low-latency software capable of managing the simultaneous operation of all five fingers, the STM32F439IIT6 has been chosen. It offers up to 168 I/O ports, an ARM 32-bit Cortex-M4 CPU, 2 MB of Flash memory, and up to 256+4 kB of SRAM. Since the SNN is trained offline, the parameters of the

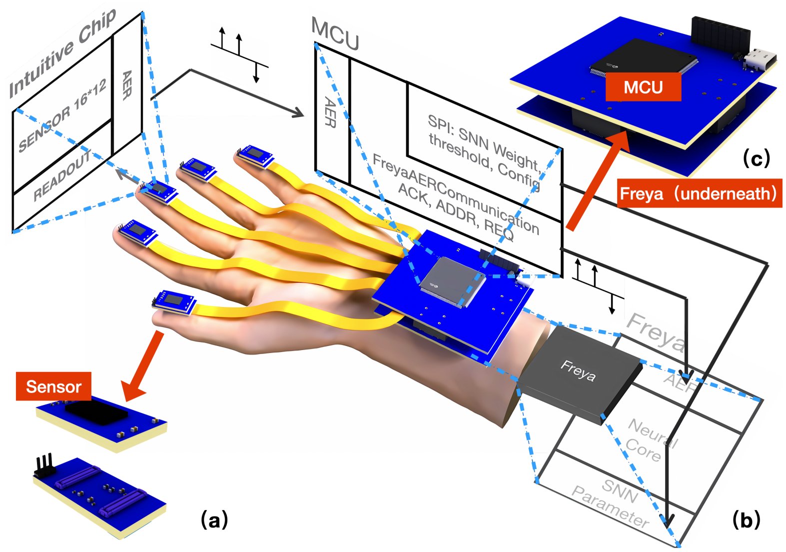

Fig. 2. A 3D illustration of the prototype hardware system as it is envisioned be positioned on a human hand. a) There are two small stacked PCBs on each finger for the INTUITIVE chip. b) On the wrist, there are two other large stacked PCBs, indicating the locations of the MCU and the c) Freya chip.

pre-trained SNN model are then loaded to Freya via the Serial Peripheral Interface (SPI). Lastly, the wrist board is equipped with a USB interface hardware for power supply and communications.

Software Due to the simultaneous input from the five per-finger INTUITIVE chips, the software infrastructure employs a Real-Time Operating System (RTOS) on the MCU to guarantee low-latency reception of digital spike signals from all fingers. As shown in Fig.3, the system categorizes tasks into three primary levels of priority. The highest priority is given to the *readSpike* task, focused on signal acquisition from a sensor chip. Following this is the *FreyaCommunication* task, which manages read/write interactions with the SNN processor. The *preprocessSpike* task, with the lowest priority, adapts the INTUITIVE spike data for the Freya processor, involving downsampling, filtering, toFrame transformation and remapping: data from the INTUITIVE chip should be spatially downsampled to reduce its spatial dimensions, thereby conserving neuron resources for the hidden layer of Freya; data need to be filtered to remove noise; data need toFrame transformation to adapt the Freya AER protocol, aligning and integrating multiple spikes over time into a cohesive data representation; data need to be remapped to shift from the 8bit signal lines of INTUITIVE to the 11bit signal lines of Freya.

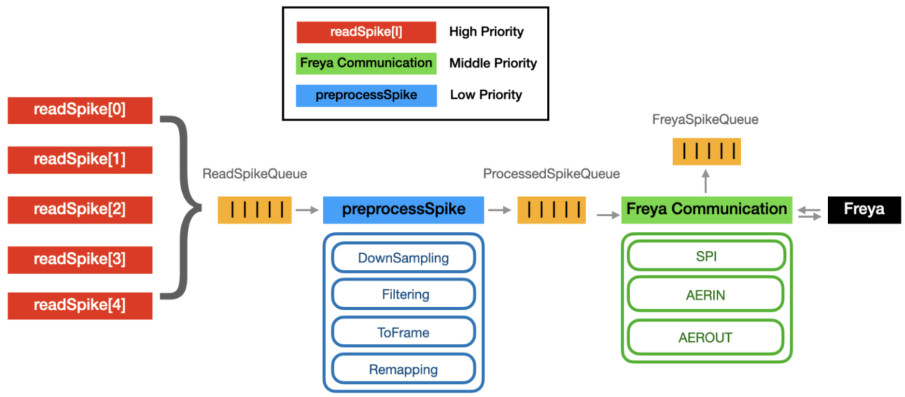

Fig. 3. The software architecture on the MCU, with high-priority tasks shown in red, medium-priority tasks in green, and low-priority tasks in blue.

4 Integration Challenges

4.1 Chip Protection

The INTUITIVE chip requires specialized encapsulation and chip packaging (see Fig. 2(a)) to ensure its durability from mechanical wear-and-tear without a substantial reduction in its sensing sensitivity. Given these constraints, the following chip protection strategies are adopted: (a) Z-axis PCB milling and (b) UV-cured epoxy encapsulation. The milling step is needed to mount the INTUITIVE chip on a cavity on the board (Fig. 4(a)), resulting in the chip and the board's top layers to be on the same level. This then allows to both shorten and reduce the heights of the chip-to-PCB bondwire connections. Secondly, the UV-cured epoxy encapsulation (Fig. 4(b)) is applied manually through a micro-pipette to cover the bondwires while preserving the opening to the chip's active sensing area. The board cavity resulting from the milling further prevents the compliant pre-cured epoxy to spread over the active sensing area.

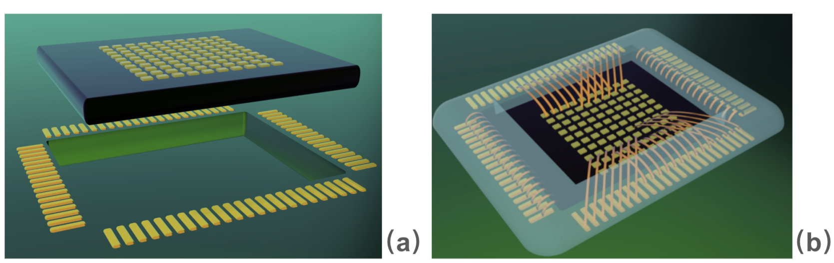

Fig. 4. (a) Z-axis PCB milling (b) UV-cured epoxy encapsulation.

4.2 High-Voltage Poling

To enhance the integrated piezoelectric sensor array's sensitivity, a poling procedure needs to be performed. This process, used to align the dipoles that are randomly oriented during the deposition, involves applying a 10-Hz, 25-V_{amp} sinusoidal signal across the sensors. As the high-voltage nature of the poling voltage signal could damage both the chip and the on-board circuitry, the following strategies have been implemented: (a) integrating on-chip per-taxel configurable switches for proper bottom electrode grounding, and (b) board stacking to allow physical disconnection during the poling of the board, which isolates the INTUITIVE chip from the rest of the system.

5 Conclusion

A neuromorphic tactile sensing platform has been proposed that combines a high-spatial-resolution spiking tactile sensor readout chip with a digital spiking neural network processor. Both the tactile sensing and processing chips utilize event-driven approaches, thus mimicing the power-efficient sensing and processing seen in the human somatosensory system and the brain. The proposed platform, which provides the necessary signal conditioning, power delivery, and data handling, will then enable real-life and real-time tactile sensing experiments in the future, therefore, presents a path towards demonstrating its applicability in future robotic and prosthetic applications.

References

1. Bartolozzi, C., Natale, L., Nori, F., Metta, G.: Robots with a sense of touch. Nature materials **15**(9), 921–925 (2016)
2. Corniani, G., Saal, H.P.: Tactile innervation densities across the whole body. Journal of Neurophysiology **124**(4), 1229–1240 (2020)
3. Lee, W.W., Tan, Y.J., Yao, H., Li, S., See, H.H., Hon, M., Ng, K.A., Xiong, B., Ho, J.S., Tee, B.C.: A neuro-inspired artificial peripheral nervous system for scalable electronic skins. Science Robotics **4**(32), eaax2198 (2019)
4. Taunyazov, T., Sng, W., See, H.H., Lim, B., andAbdul Fatir Ansari, J.K., Tee, B., Soh, H.: Event-driven visual-tactile sensing and learning for robots. In: Proceedings of Robotics: Science and Systems (July 2020)
5. Alea, M.D., Safa, A., Assche, J.V., Gielen, G.G.E.: Power-efficient and accurate texture sensing using spiking readouts for high-density e-skins. In: 2022 IEEE Biomedical Circuits and Systems Conference (BioCAS). pp. 359–363 (2022)
6. Alea, M.D., Safa, A., Giacomozzi, F., Adami, A., Temel, I.R., Lorenzelli, L., Gielen, G.: A fingertip-mimicking 12×16 200μm-resolution e-skin taxel readout chip with per-taxel spiking readout and embedded receptive field processing. In: 2023 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits). pp. 1–2 (2023)
7. Frenkel, C., Lefebvre, M., Legat, J.D., Bol, D.: A 0.086-mm^2 12.7-pj/sop 64k-synapse 256-neuron online-learning digital spiking neuromorphic processor in 28-nm cmos. IEEE Transactions on Biomedical Circuits and Systems **13**(1), 145–158 (2019)