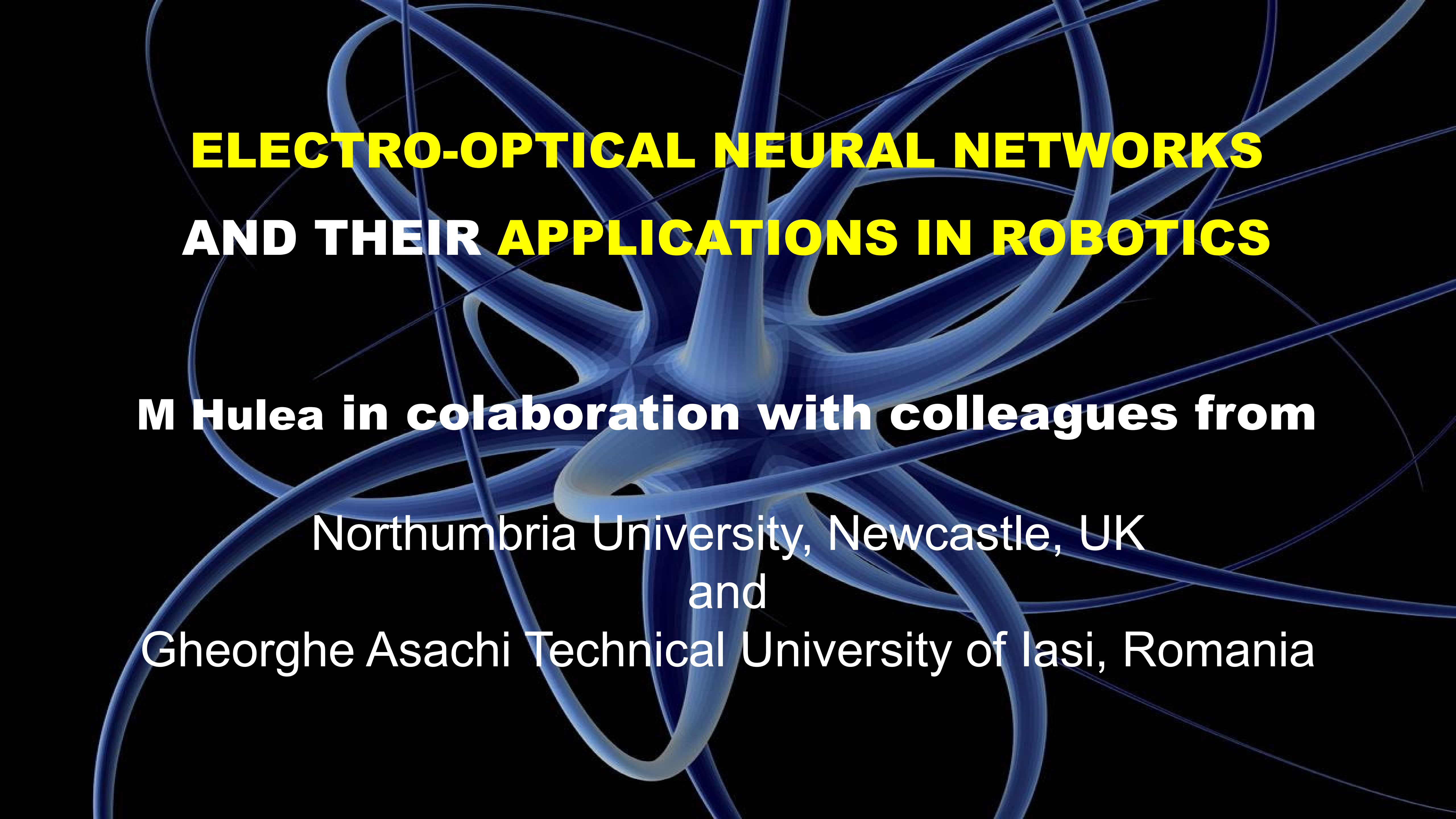


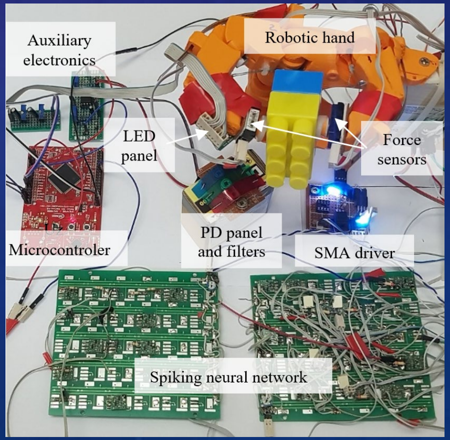
ELECTRO-OPTICAL NEURAL NETWORKS AND THEIR APPLICATIONS IN ROBOTICS

M Hulea in colaboration with colleagues from

Northumbria University, Newcastle, UK
and
Gheorghe Asachi Technical University of Iasi, Romania

RESEARCH DIRECTIONS

- **Control of SMA using SNN and force control**
- **Neuromorphic sensors with visible light communications**
- **Wavelength division multiplexing (WDM)**
- **Pulse amplitude modulation (PAM) with automatic gain**
- **Conclusions**
- **Future directions**



BIOLOGICAL BACKGROUND

- Muscle control is one of the most important functions of the cerebral cortex
    - Provides the organisms with the ability to mechanically interact with the external environment
- Muscle control is bidirectional (in biology)
    - Muscles contraction is determined by the spiking frequency of the motor neurons
    - Neural network receives input related to elongation and contraction force from the spindles
- Limbs movements
    - Multiple muscles are controlled by the central pattern generators (CPG)

FORCE CONTROL USING SMA ACTUATORS AND SNN

Complex task:

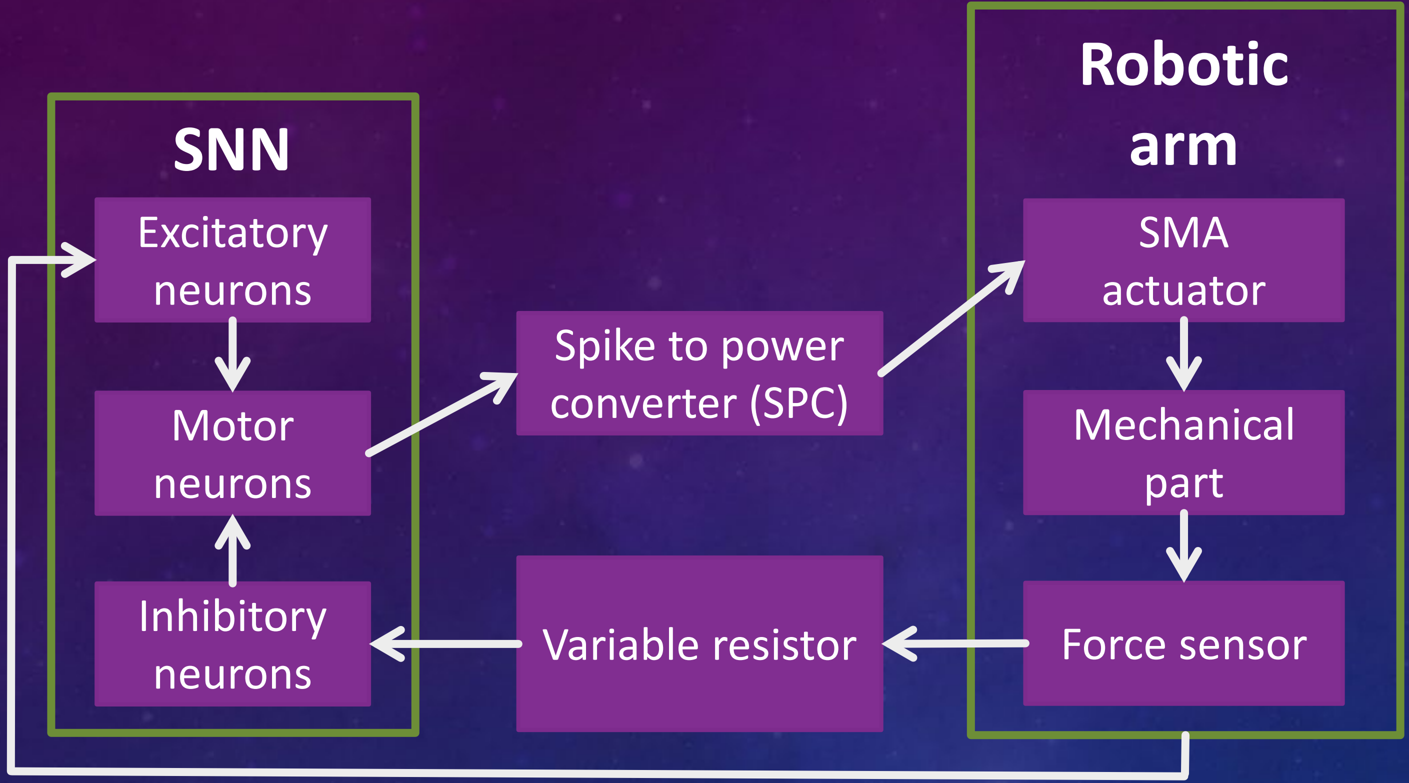
- humanoid robots → artificial hand and fingers
- Smoothness, precision, accuracy of the natural motions
- Implementation of a **bioinspired system** that is able to control **the force of artificial fingers.**
  - Spiking neural network → **biologically inspired neuron** model implemented in analogue hardware
  - **Muscles** → **shape memory alloy** (SMA) Flexinol actuator wires
  - Neural network **structure** → inspired from lamprey motor neural areas

BIOINSPIRED ANALOGUE SYSTEM DESIGN

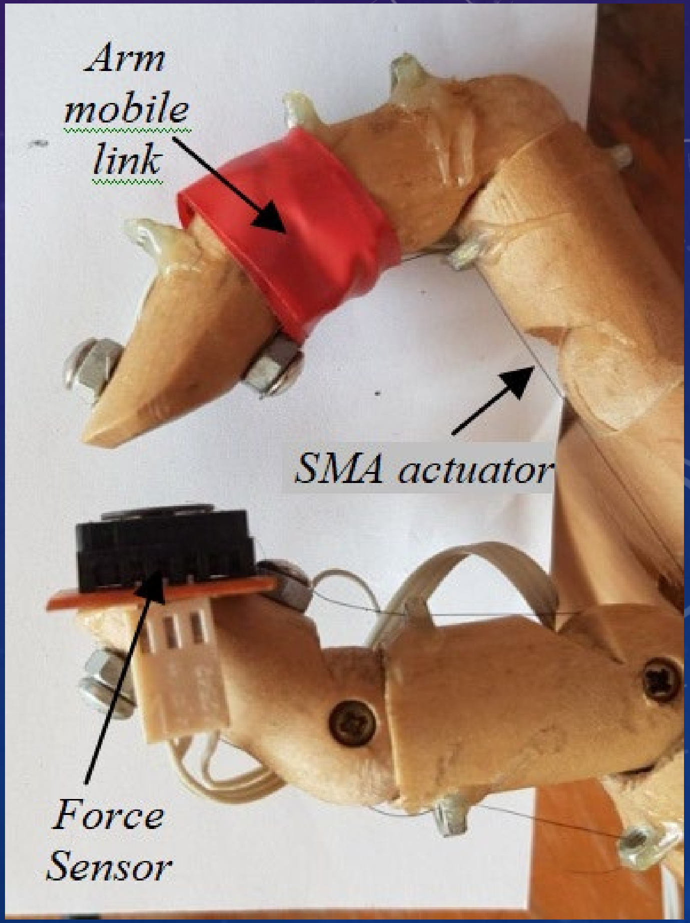
- **Spiking neurons** → the most accurate model of the biological neurons
- **SNN for motion control** → microcontrollers, FPGA (faster prototyping, slower response)
- **Analogue circuits** → better alternative (physical similarities) such as:
  - Full parallel operation
  - Full parallel information transmission
  - Infinite **resolution** for the variation of the internal signals

  => complex function implementation
  - Very low power consumption
  - High reliability

GENERAL CONCEPT

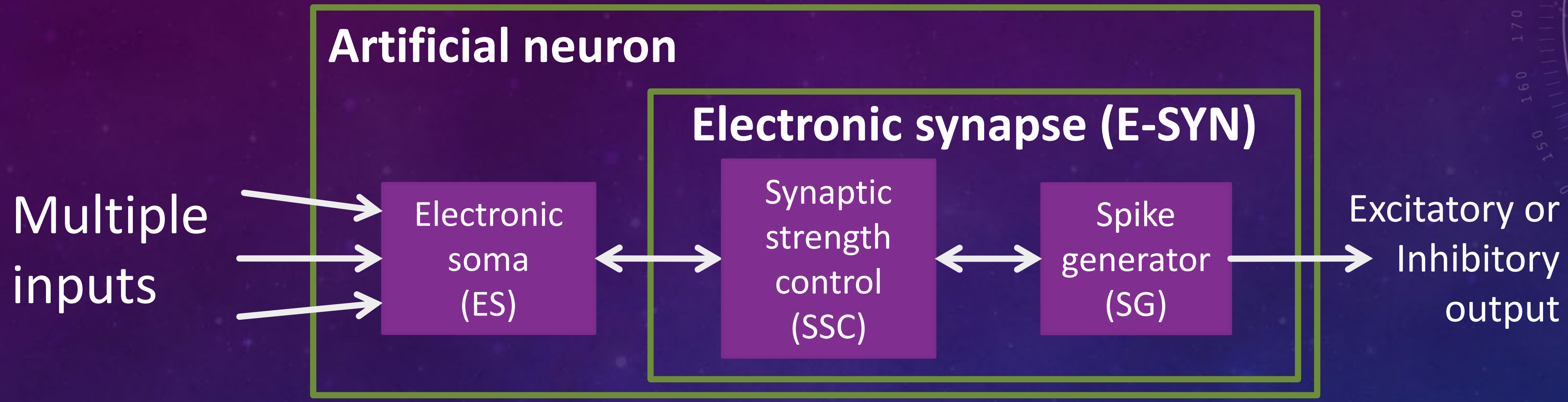


- Two opposing fingers that are actuated by SMA actuators



- **Robotic fingers**:
  - Flexed by SMA actuators
  - SMA contracts because of heating
  - Force sensor stops the finger motion

ELECTRONIC NEURON



Artificial neuron

Electronic synapse (E-SYN)

Multiple inputs

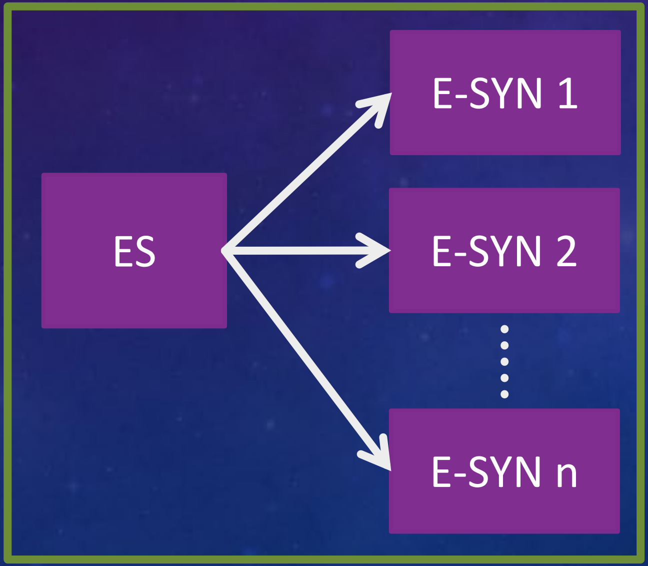
Electronic soma (ES)

Synaptic strength control (SSC)

Spike generator (SG)

Excitatory or Inhibitory output

One electronic soma can be connected to more electronic synapses



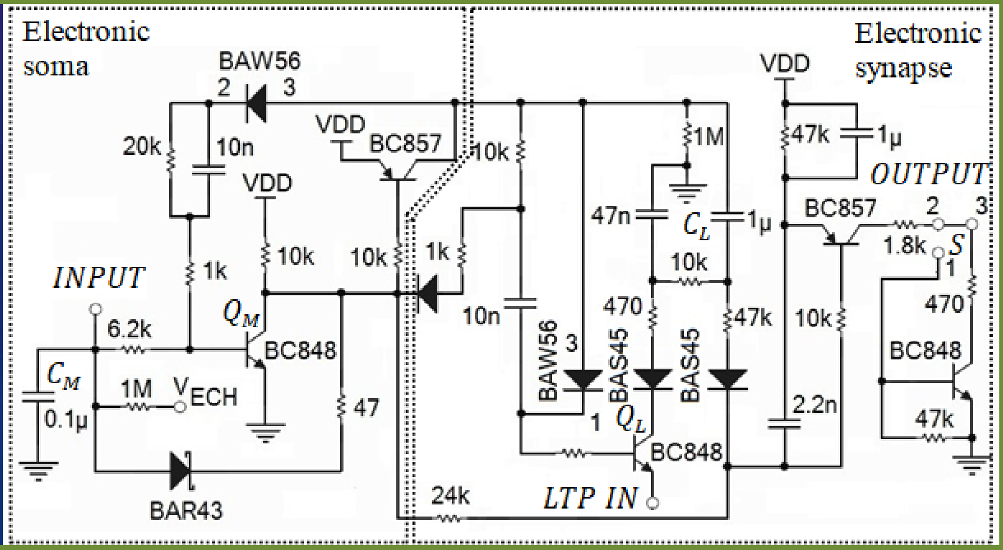
ES

E-SYN 1

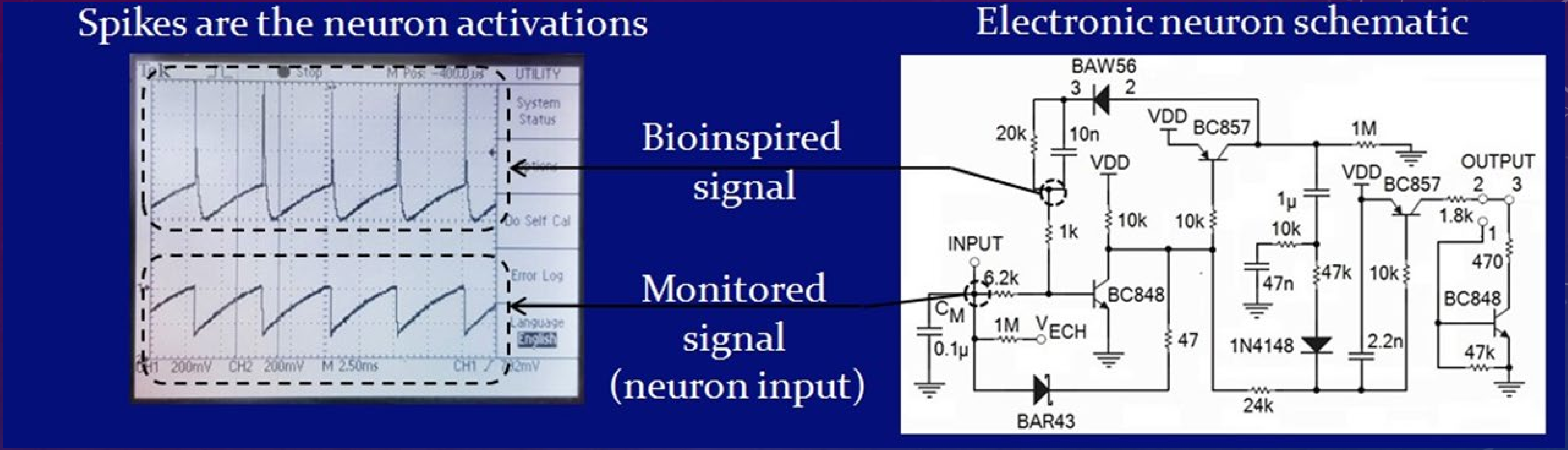
E-SYN 2

E-SYN n

Artificial neuron



ELECTRONIC NEURON OPERATION



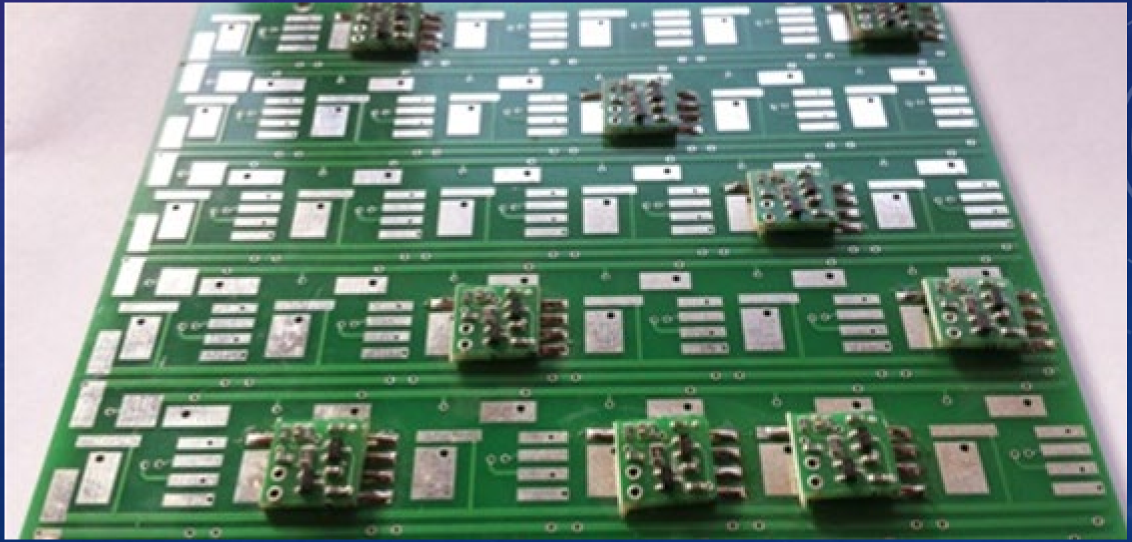
Spikes are the neuron activations

Electronic neuron schematic

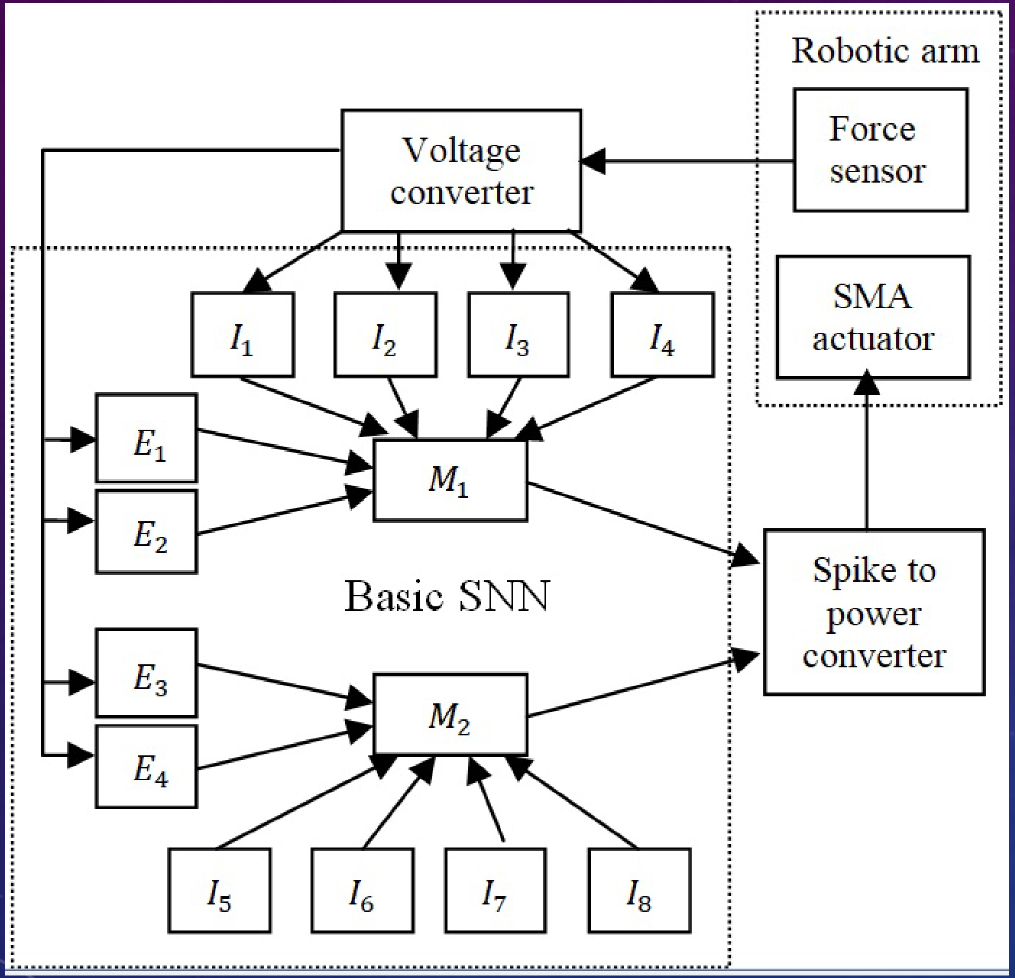
Bioinspired signal

Monitored signal (neuron input)

- PCB implementation of unconnected neurons



NEURAL NETWORK

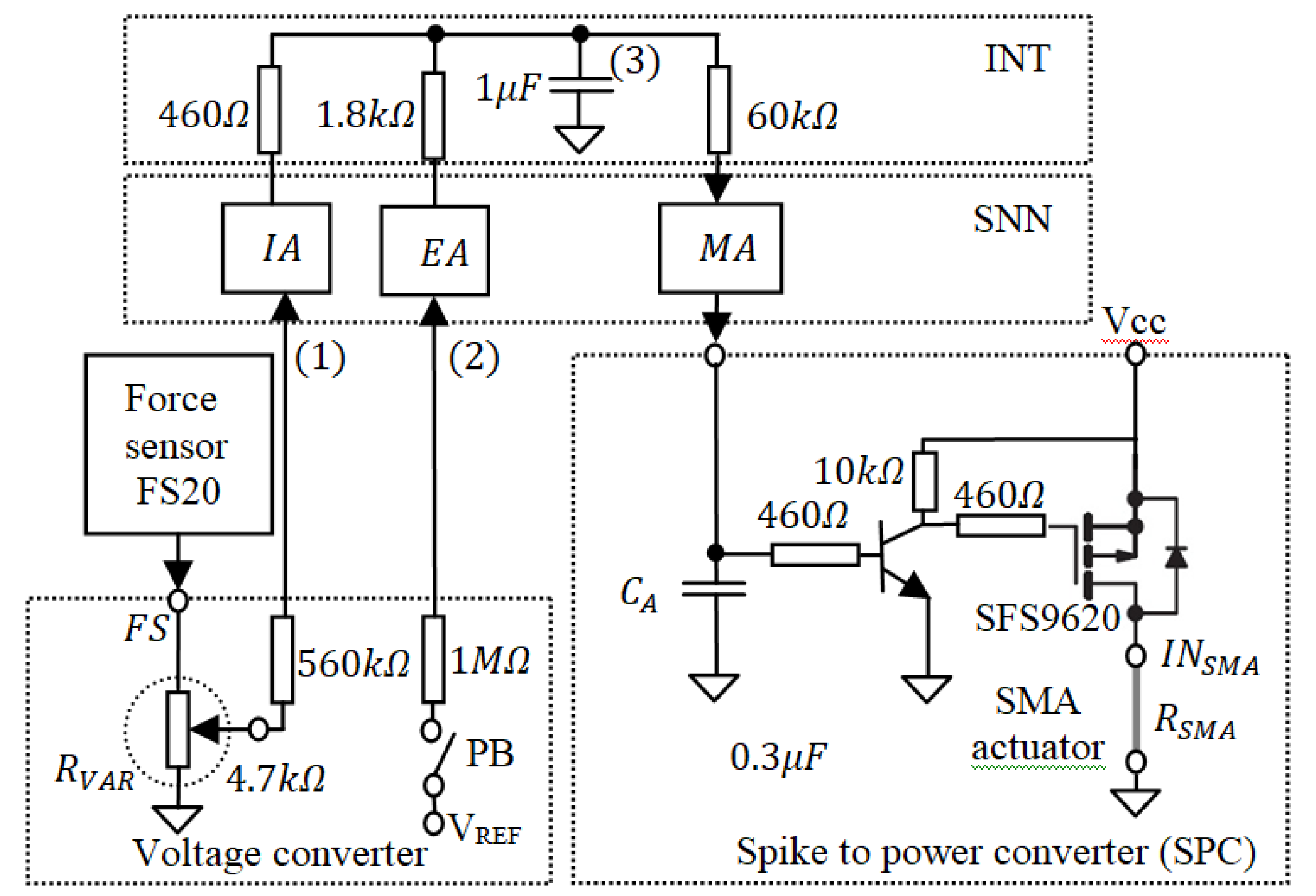


Basic SNN includes:

- two motor neurons (M)
- 4 excitatory neurons (E)
- 8 inhibitory neurons (I)

- SMA actuator is driven by the SPC
- Integrated excitatory output of M
- Inhibitory neurons stimulated by FS
- SNN controls the contraction force

STRUCTURE OF THE BIOINSPIRED SYSTEM



ANALOGUE ELECTRONICS

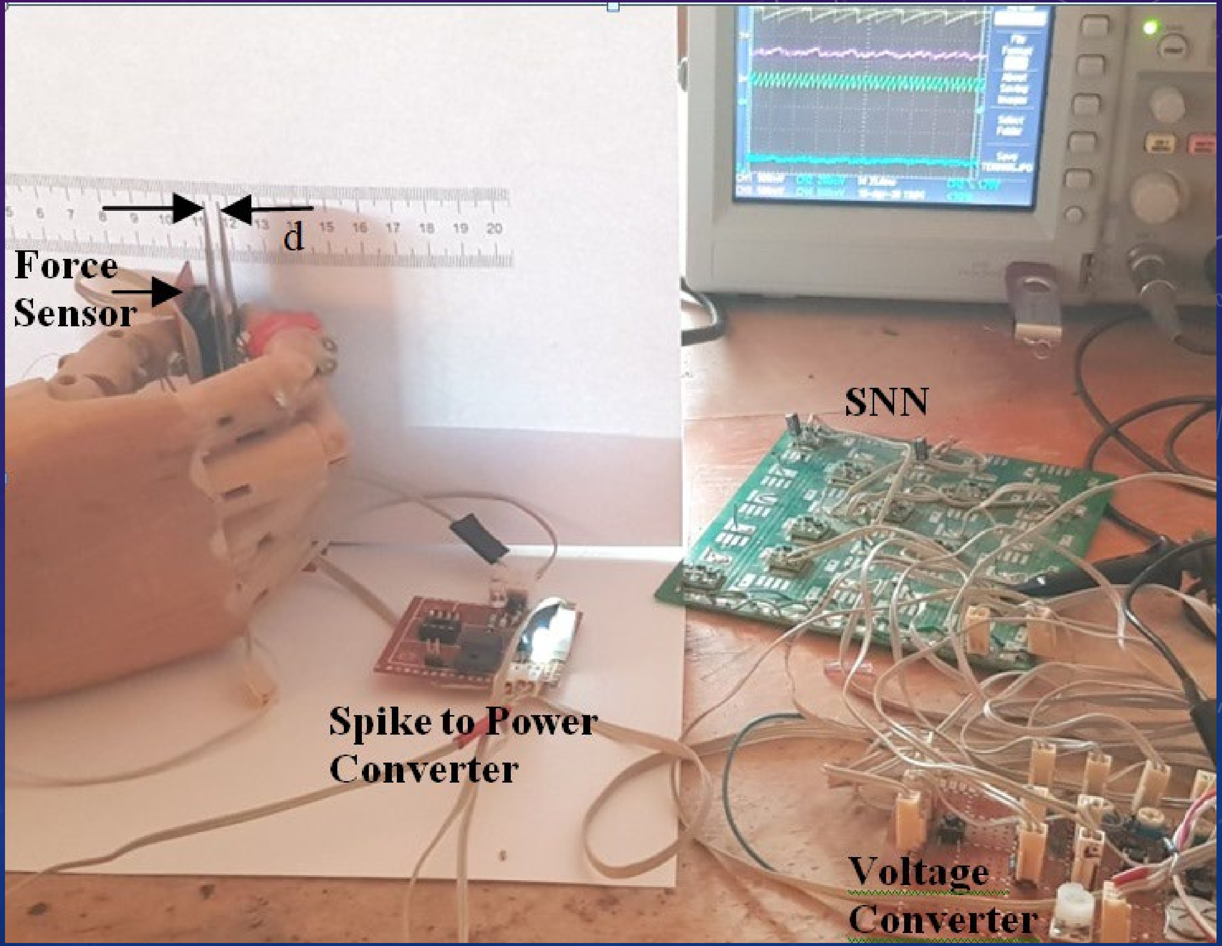
- Voltage converter
- Spike to power converter
- Integrator (INT)

- SMA converts current into force
- Force sensor (FS) converts force into voltage

PROTOTYPE OF BIOINSPIRED SYSTEM

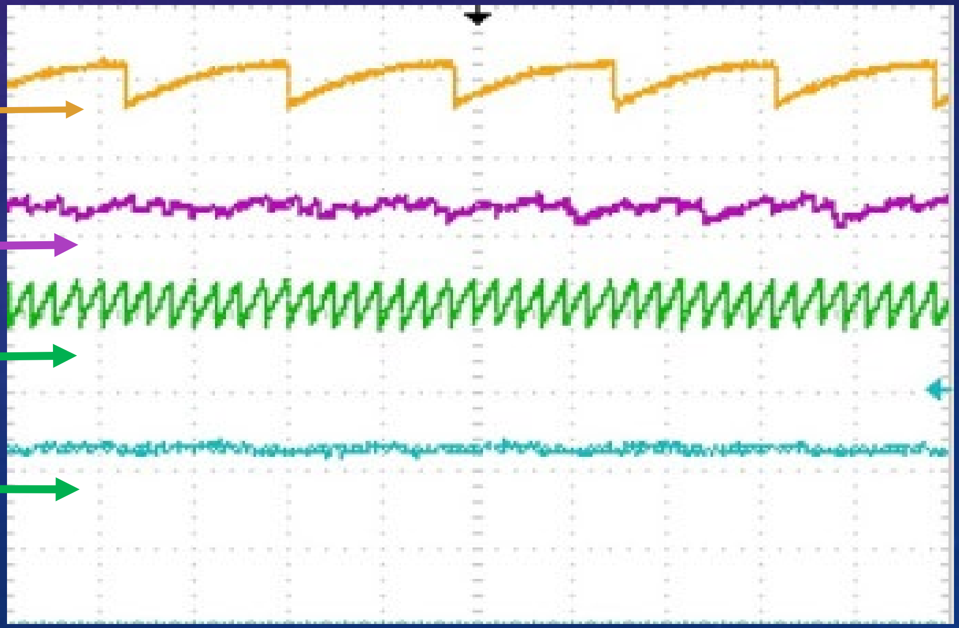
Experimental setup:

- Robotic hand holding a tweeters
  - Distance between heads (d)
- Spiking neural network
- Auxiliary electronics
  - Spike to power converter
  - Voltage converter



RESULTS

- **The following tests were performed:**
  - Force sensor response
  - Possibility to adjust force strength by adjusting system parameters
  - Regulatory performance of the neural network



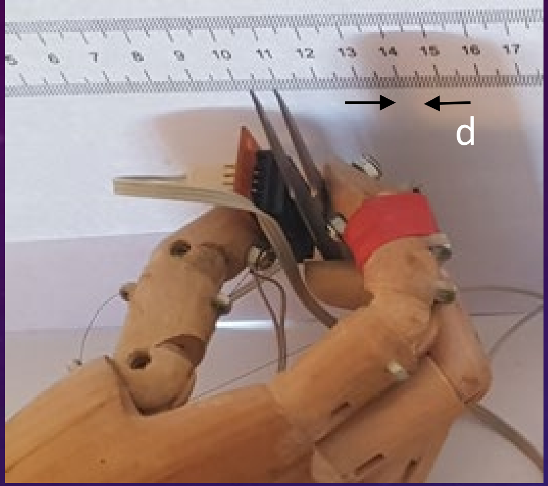
Inhibitory activity

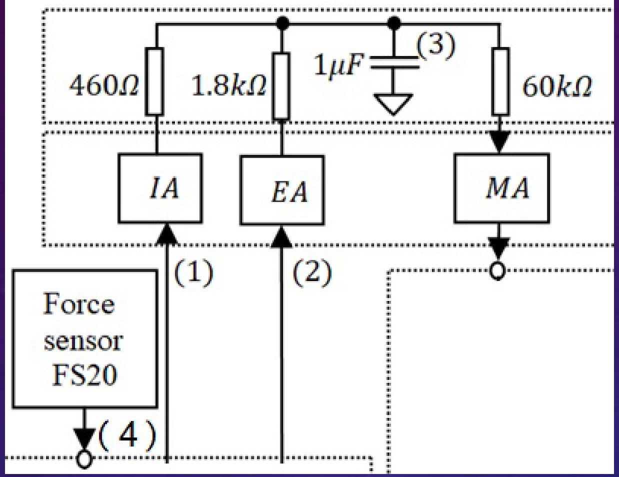
Motor input

Excitatory

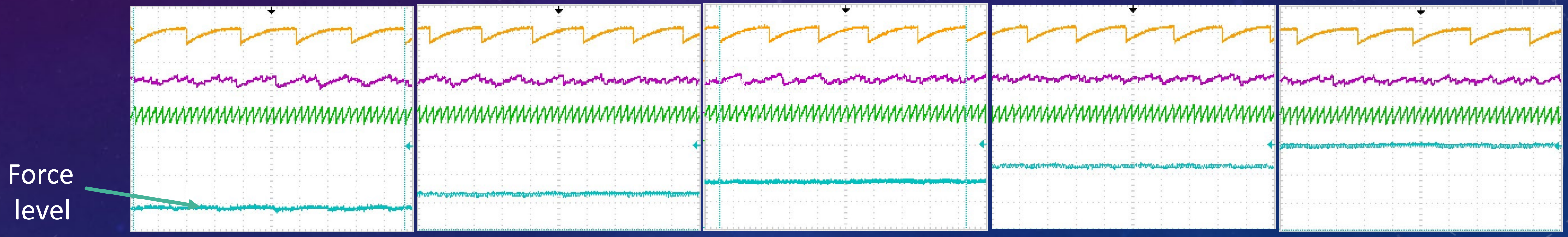
Force Level (V_J)

RESULTS





- Observations:
  - Higher motor frequency generates more force
  - Frequency of the inhibitory neurons oscillates



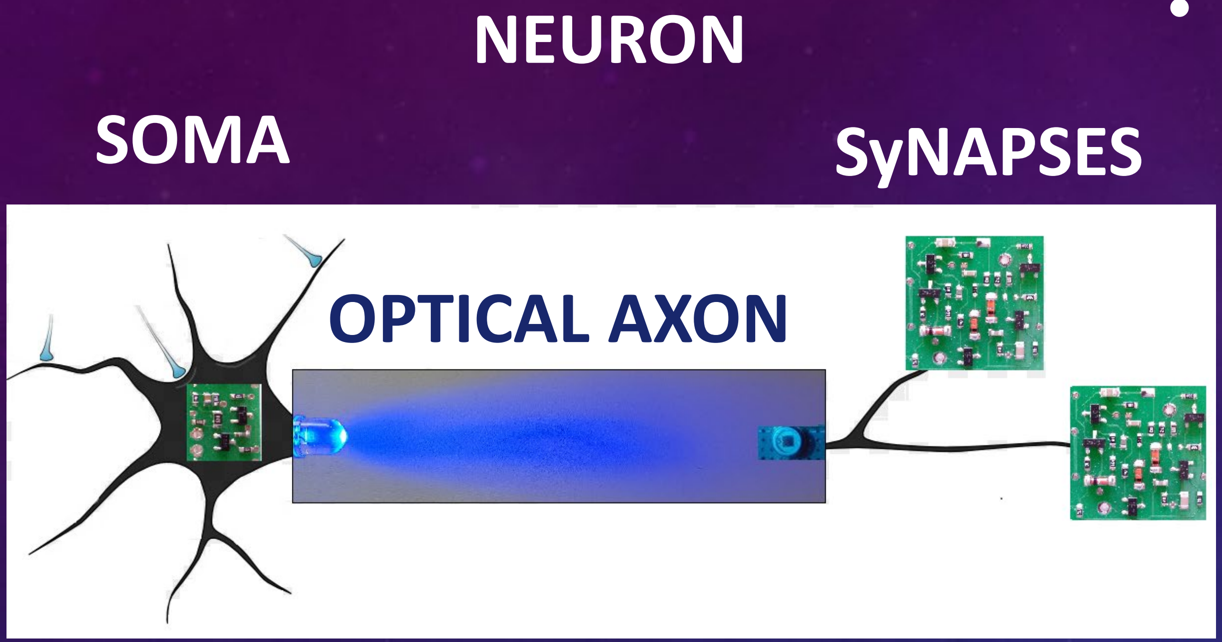
d = 4 mm
d = 3 mm
d = 2 mm
d = 1 mm
d = 0 mm

Force increases

THUS … THE SNN IS SMALL

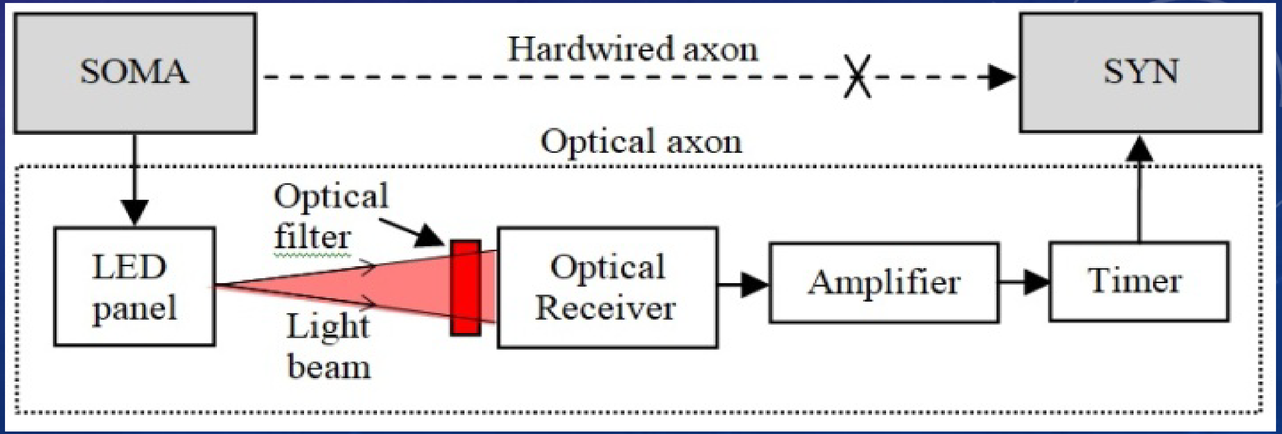
- The SNN includes a **few excitatory neurons** that determine SMA **actuator contraction**
- And a few **inhibitory neurons** that are driven by a **force sensor**
- With a few neurons SNN is able to control the force applied on an object by the two opposing fingers
- SNN is a good regulator for the contraction force of SMA actuators

WIRELESS CONNECTIVITY IN SNN



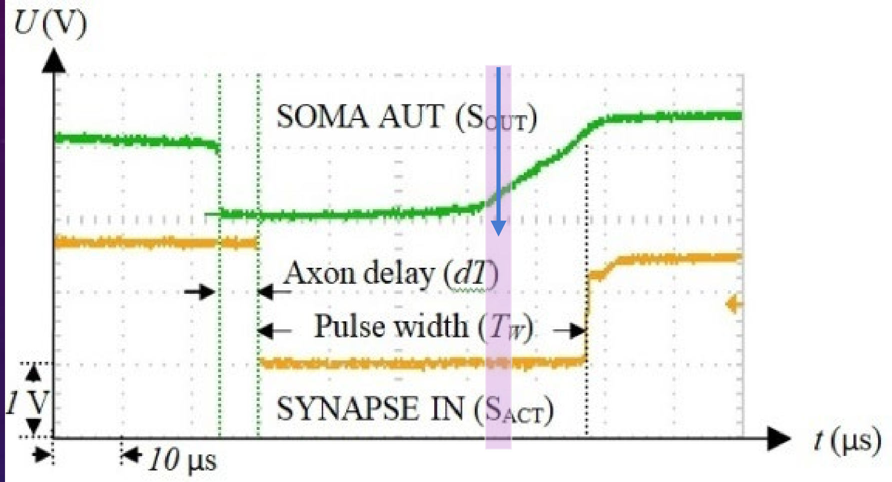
- **Advantages**
  - Tolerant to optical signal fading due to OPL and misalignment α variation
  - Implementation of optical connections between distanced neural areas (<190 cm)
  - Neural areas are in relative motion

- Evaluate the influence of:
  - The optical axon on the spike energy
  - Axon delay on SNN activity
- Optical axons – the concept

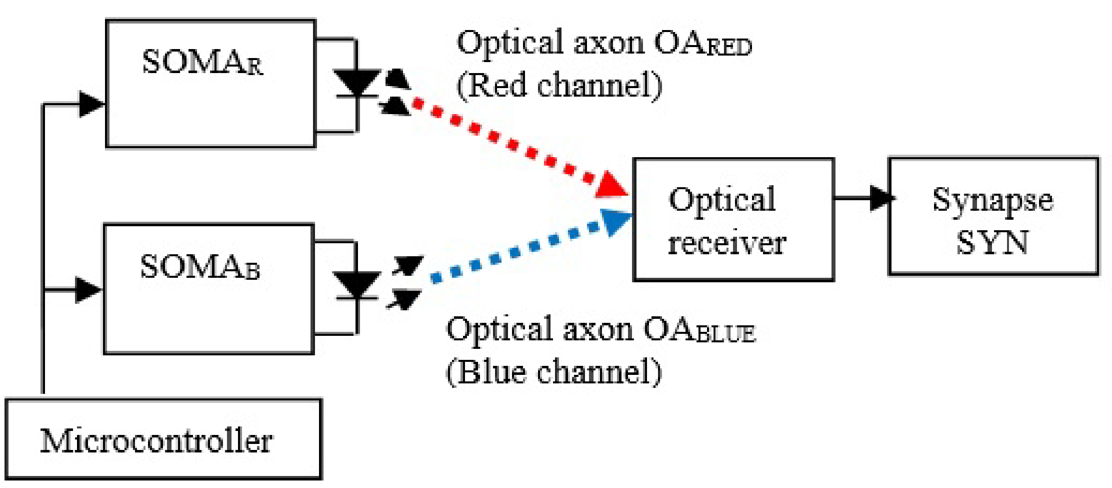


DELAY DETERMINED BY OPTICAL AXON

Delay (dT)



Experimental setup



Optical channel characteristics

- OPL varies between **5 and 190 cm**
- deviation varies between **0 and 60 °**

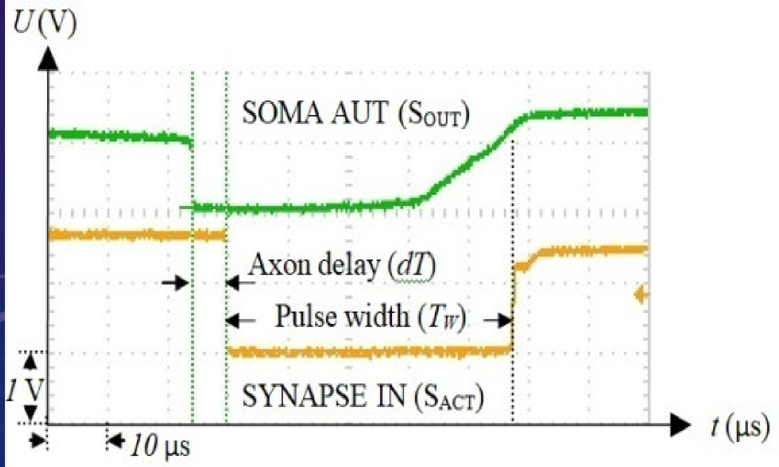
LEDs characteristics

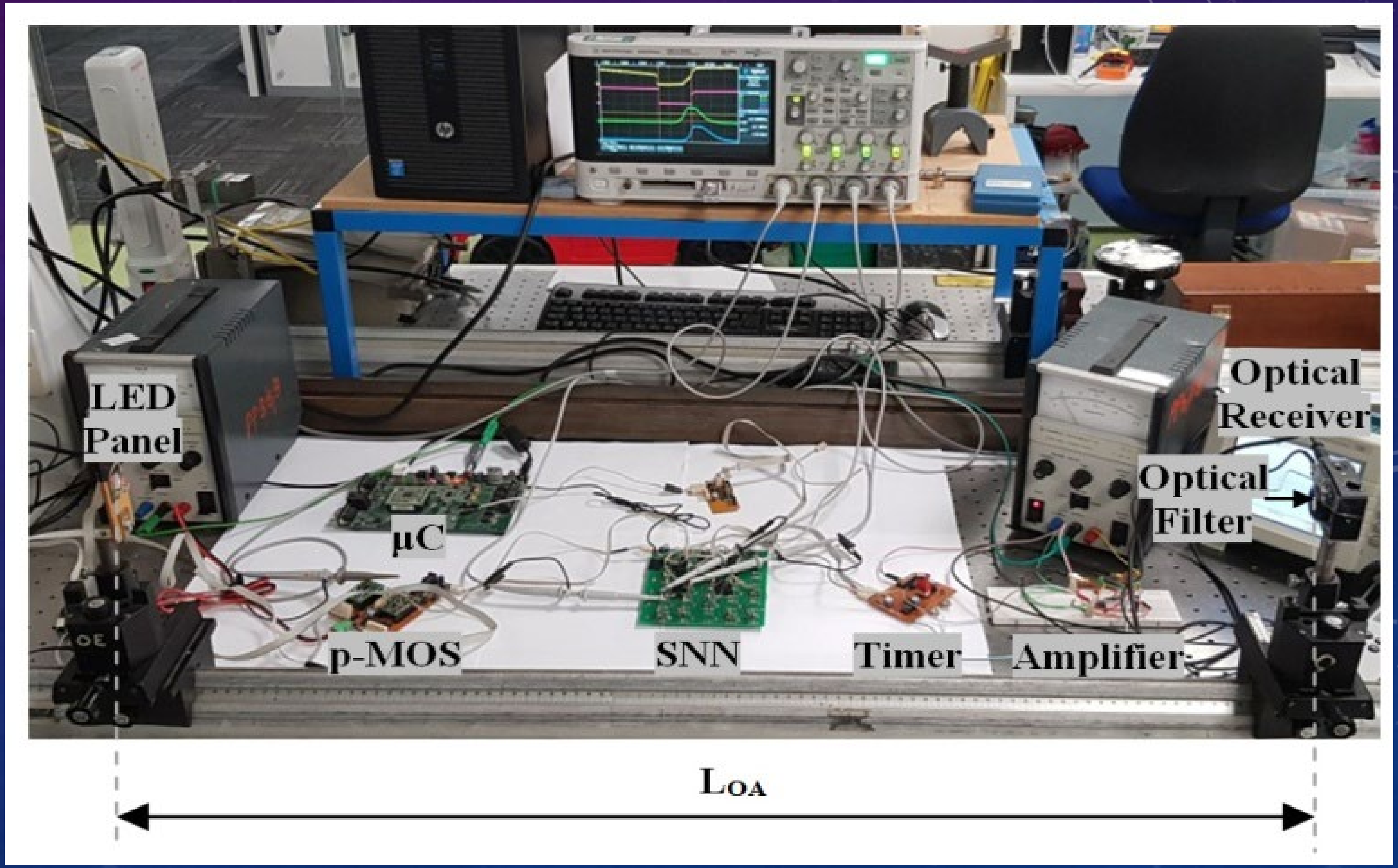
- OA RED – 640nm, FOV=125°, 460 LUX
- OA BLUE – 465nm, FOV=125°, 252 LUX

EXPERIMENTAL EVALUATION OF OPTICAL AXON

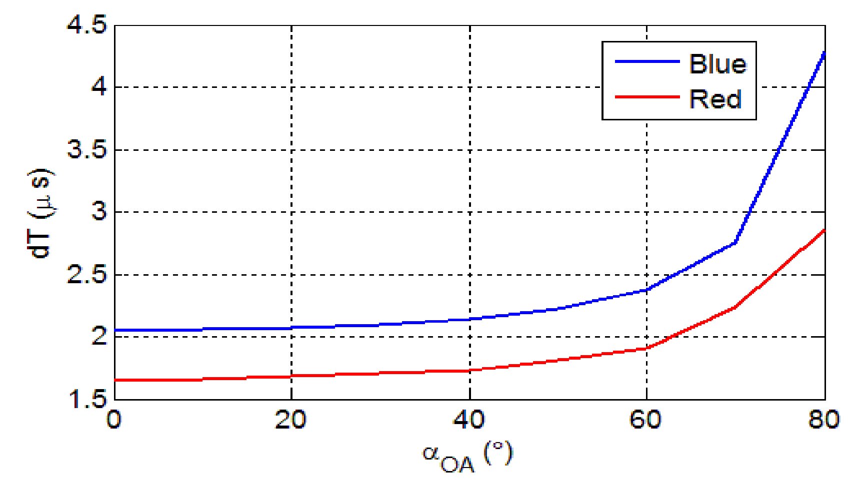
Northumbria University, United Kingdom

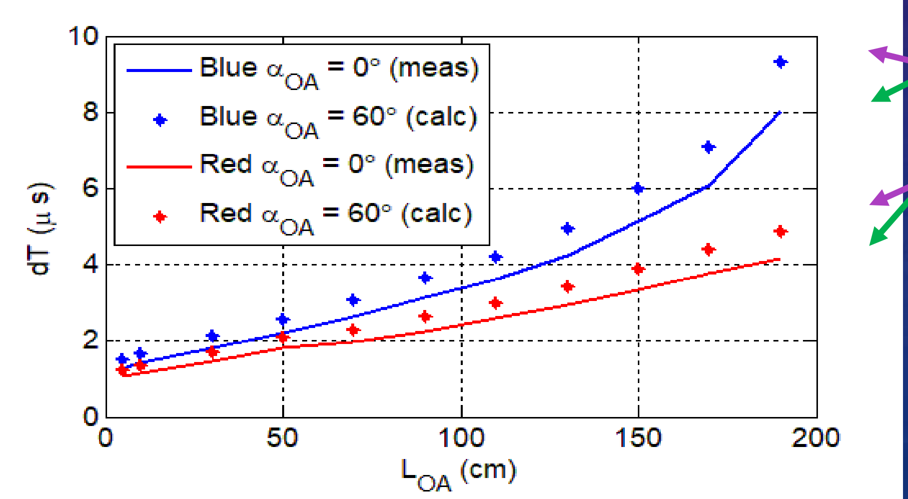
- Experimental setup
- Influence of the OPL and deviation on:
  - **Delay** introduced in neural transmission





DELAY DETERMINED BY OA





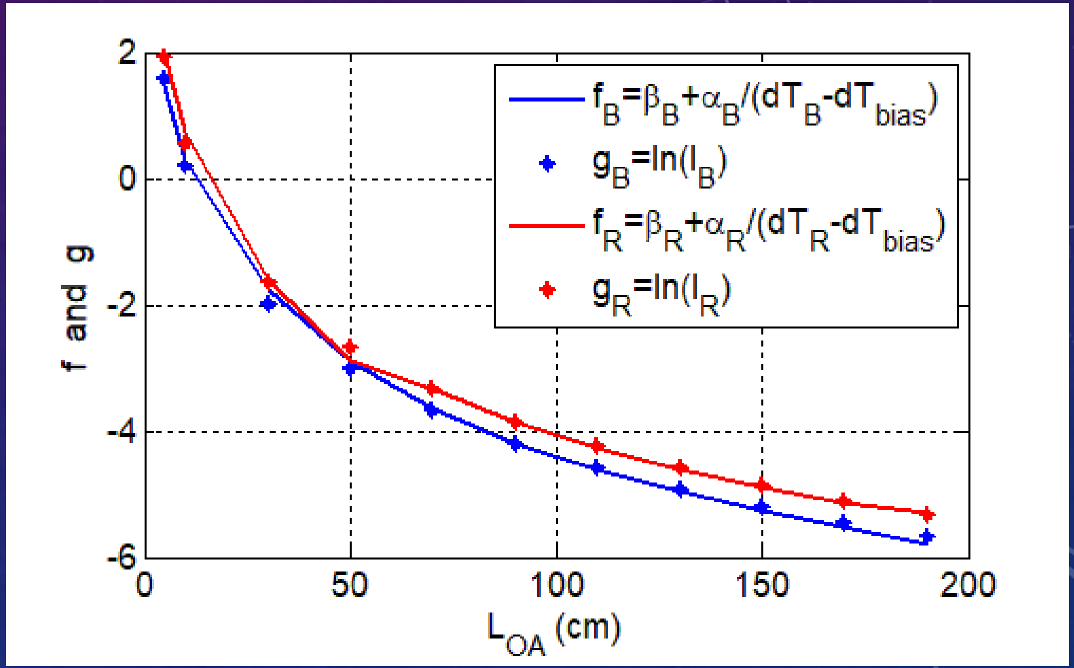
- Delay vs alignment (α)
  - **Delay increases with α and OPL**
  - **Lower E_V implies higher delay**
- Delay vs optical path length
  - Measured dT for α = 0°
  - Calculated dT for max misalignment α = 60°
  - Max delay is 8 µs for: OPL=190 cm and α = 0°

THEORETICAL ANALYSIS – DELAY CAN BE CALCULATED

$$I_{PD} = \frac{E_V}{683\ V_\lambda}\eta$$

Dots: $g = \ln(I_{\text{PD}})$

$$f = \beta + \frac{\alpha}{dT_{\text{optical}}}$$



Model for *dT* based on illuminance *E*$_V$

Line: $$dT = \frac{\alpha}{\ln(E\eta) - \beta} + dT_{\text{bias}}$$

V_λ – Photopic efficacy

η – Rx's responsivity

α, β – parameters for scaling $1/dT$ on $\ln(I_{\text{PD}})$ determined experimentally

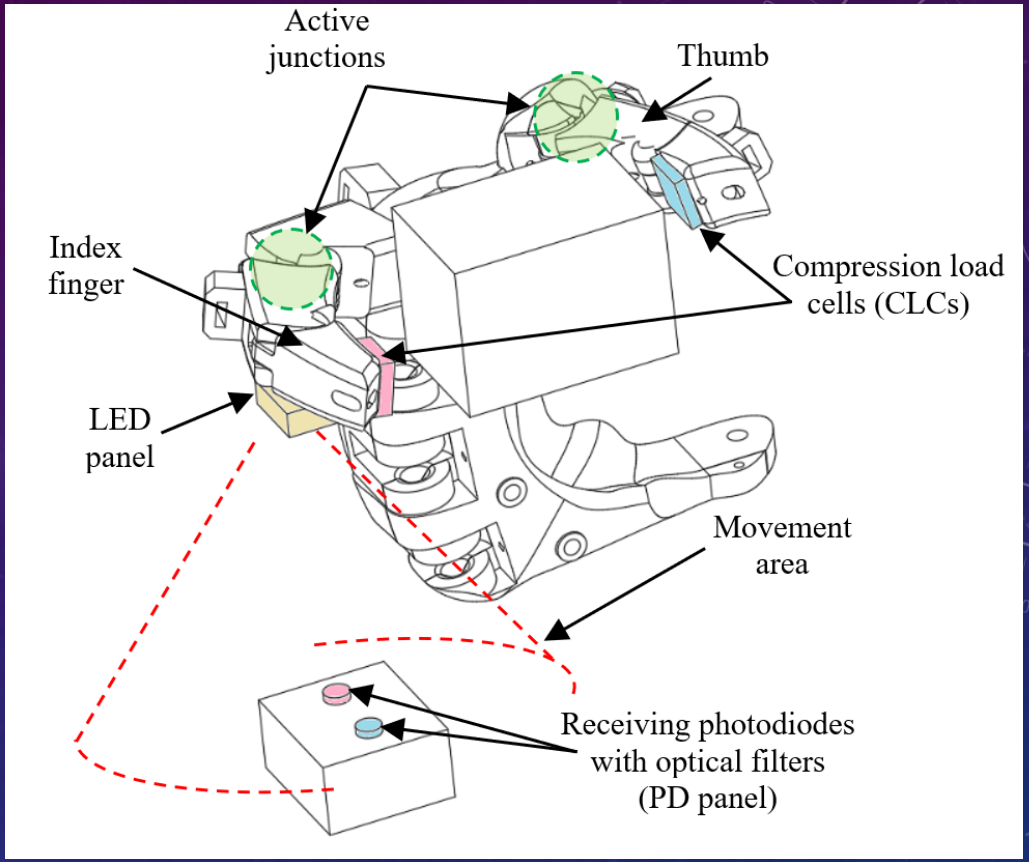
***RMS* = 0.98** for Red LED and ***RMS* = 0.95** for Blue LED

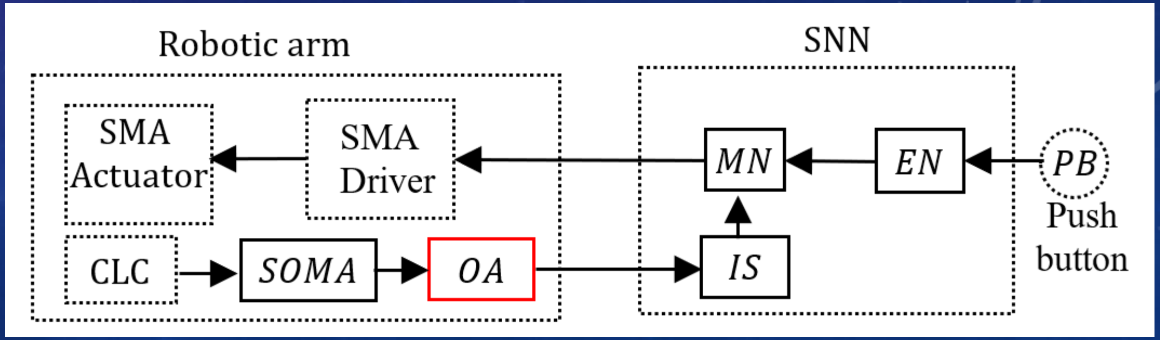
ELECTRO-OPTICAL SPIKING NEURAL NETWORKS

- Goal: **Implement parallel optical links in humanoid robots with motion tolerance**
  - From sensors towards the main SNN
- Proposed method
  - Wavelength division multiplexing: Costly, limited wavelength resolution, limited spectrum
- Proposed method
  - **Pulse Amplitude Modulation (PAM) - one wavelength**

SYSTEM STRUCTURE

- The fingers are actuated by shape memory alloy (SMA);
- The applied force is sensed by neuromorphic sensors placed on the fingertips;
- SNN drives the SMA actuators through hardwired connections and
- Receives feedback from neuromorphic sensors through **optical axons**;

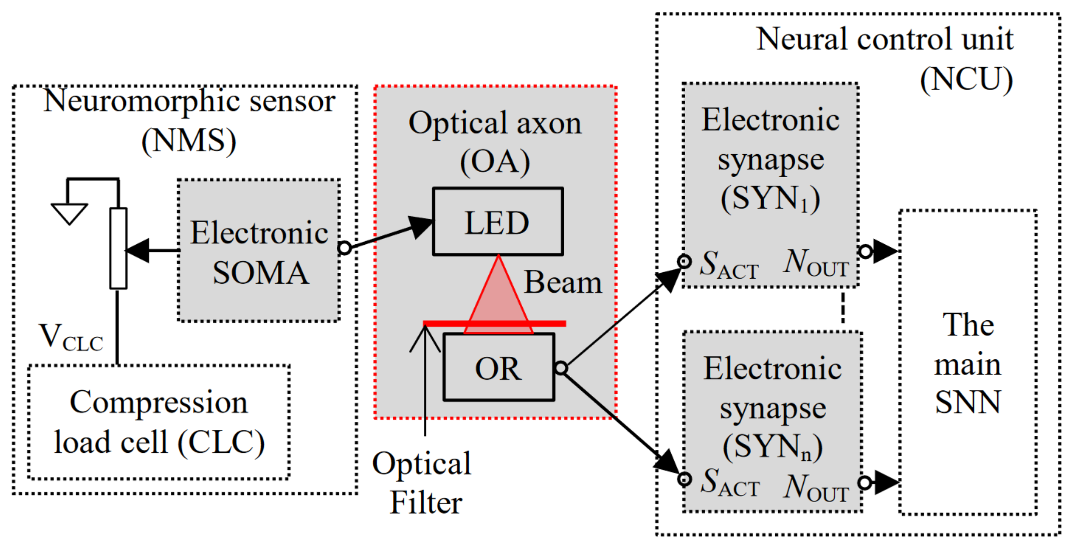




THE ELECTRO-OPTICAL SPIKING NEURON WITH OPTICAL AXONS

- Each neuron has **one SOMA** connected via the optical axons (OA) to **at least one synapse (SYN)**;
- The **synapses can generate excitatory or inhibitory spikes** to control the potential input of the postsynaptic neuron;
- The **energy of the spike signal** depends mainly on its duration, which **may vary according to the synaptic weights**;

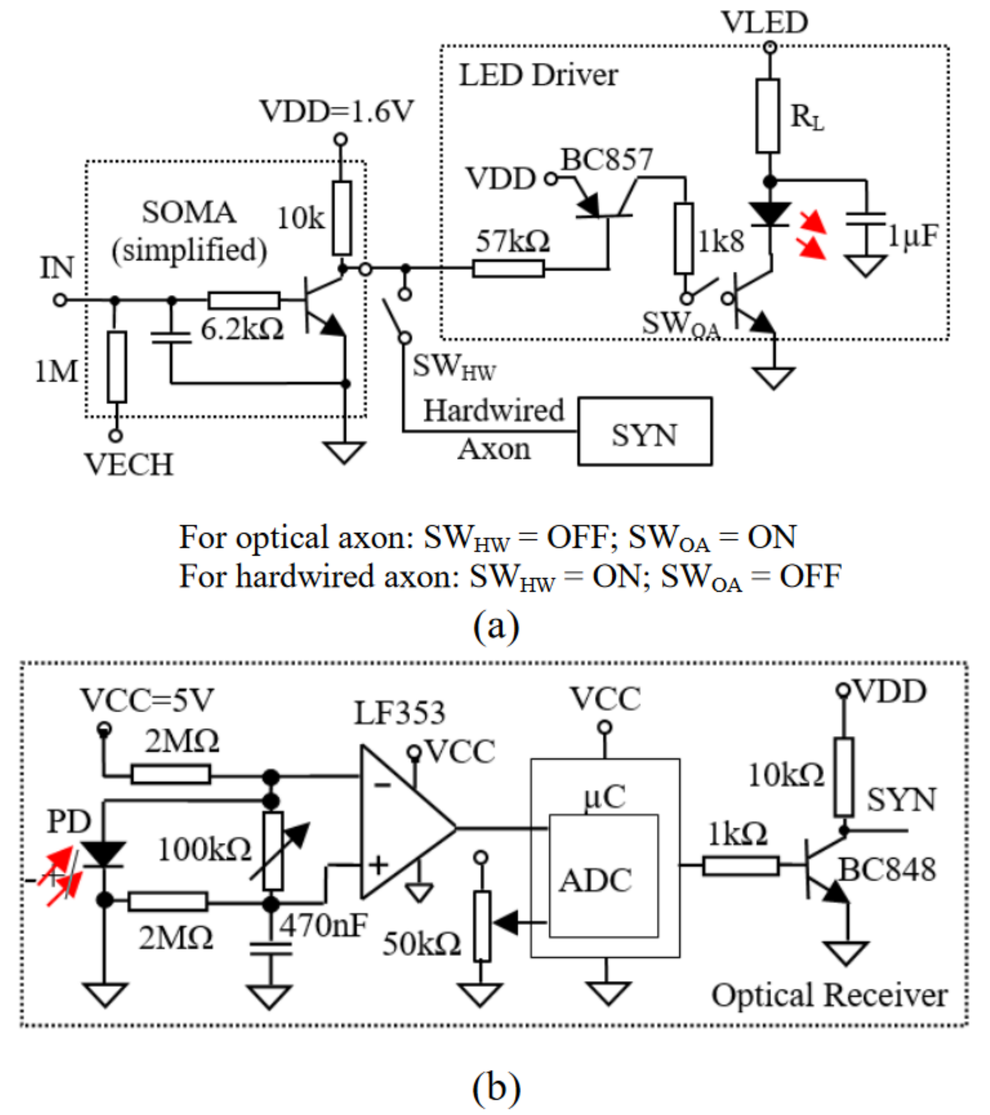
Optical axon based on wavelength division multiplexing



One wavelength per channel

THE ELECTRO-OPTICAL SPIKING NEURON

- The **transmitter (Tx) is based a LED driver**;
- The **receiver (Rx) is based** on a microcontroller that uses **an analogue to digital converter (ADC)** to read the signal



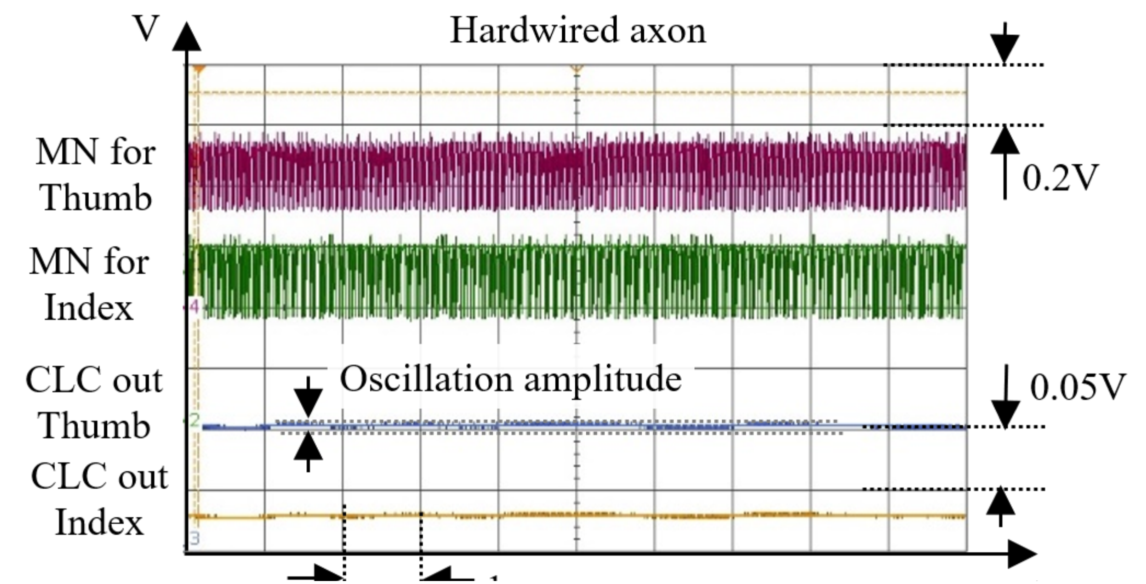
For optical axon: SW$_{HW}$ = OFF; SW$_{OA}$ = ON
For hardwired axon: SW$_{HW}$ = ON; SW$_{OA}$ = OFF

(a)

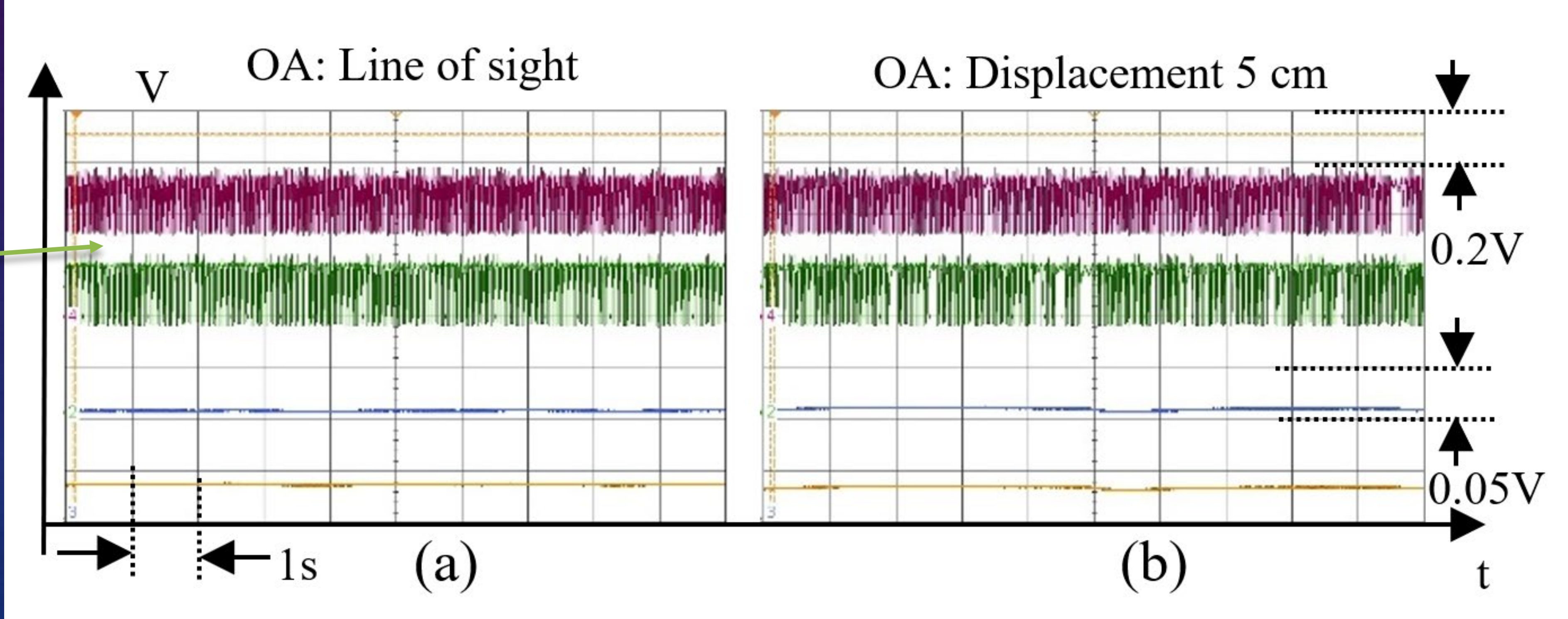
(b)

EXPERIMENTS & RESULTS WDM

- Images show the output of the CLCs for 10 seconds using a digital oscilloscope

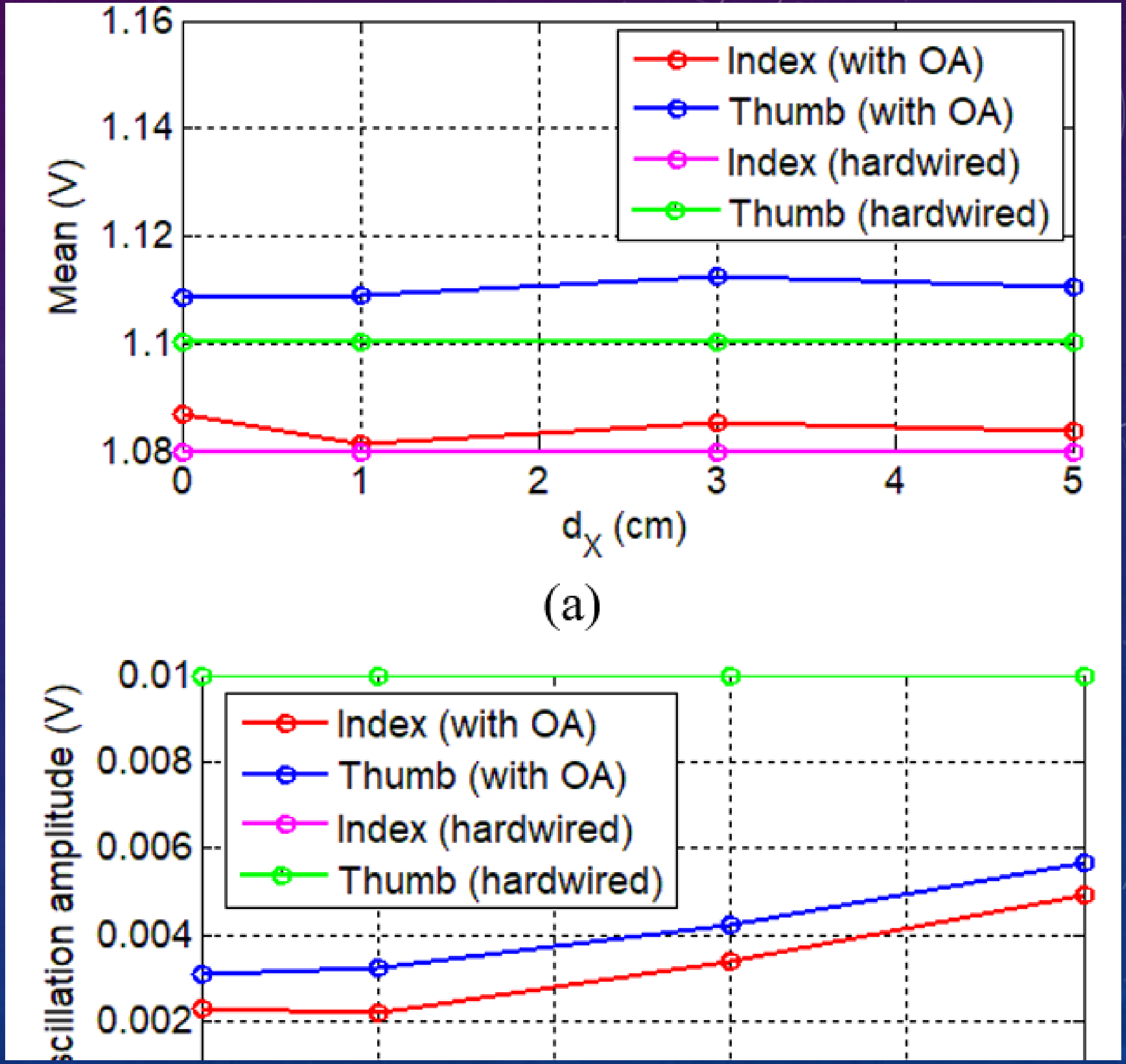


With optical connections



EXPERIMENTS & RESULTS

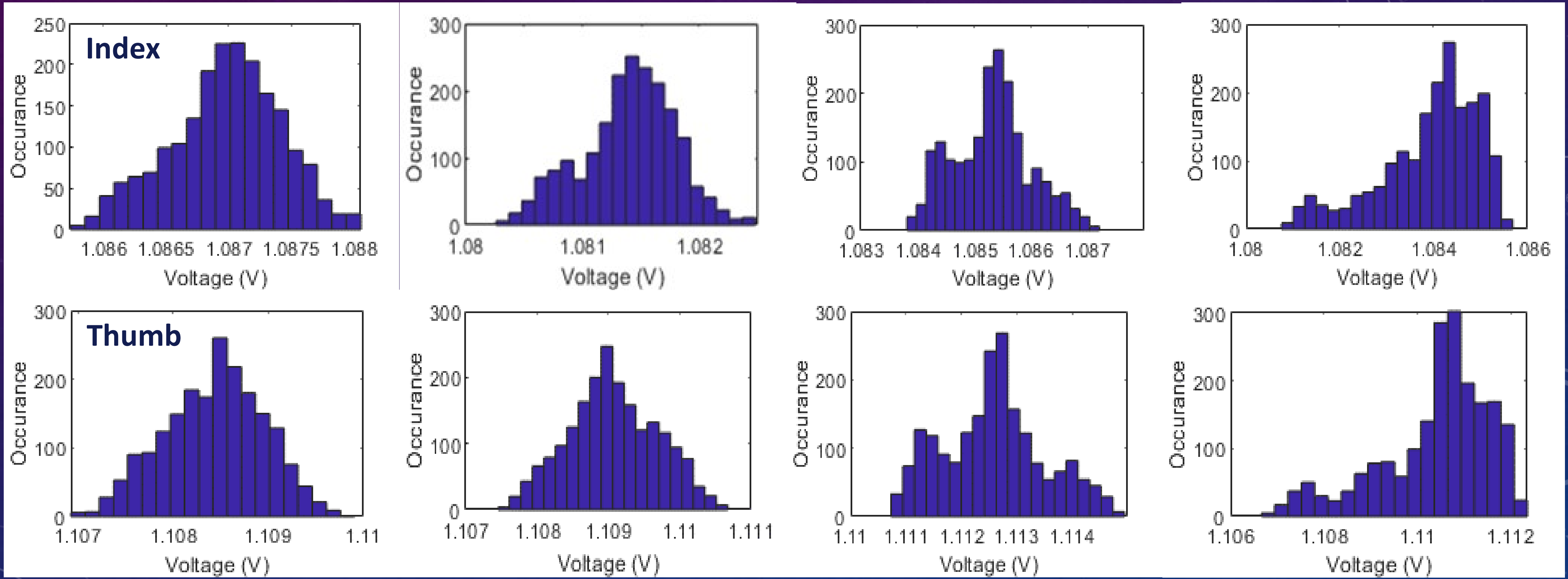
- With OA **the signal mean** varies with OPL and displacement
- However it is not clear how OA influences the fingers force
- **The oscillation amplitude** shows that the regulatory performance of the SNN is affected by the OA;
  - for certain levels of channel attenuation,



(a)

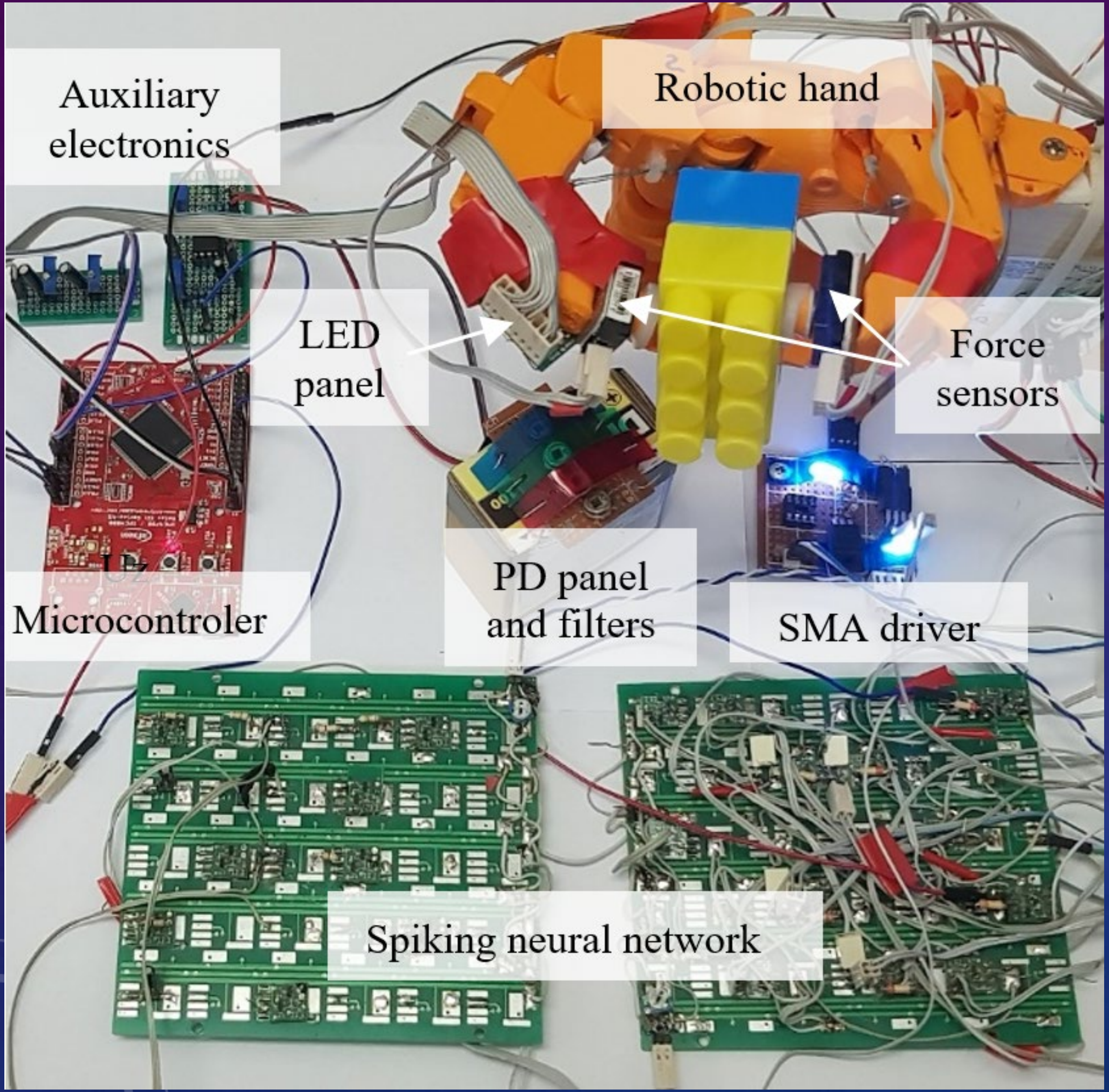
EXPERIMENTS & RESULTS

The histograms of the sensor output.



LOS ($d_x = 0$ cm) $d_x = 1$ cm $d_x = 3$ cm $d_x = 5$ cm

DISCUSSIONS



OA with WDM – one wavelength per channel

- The results demonstrated that **the influence of the proposed optical axons on the regulatory performance of the SNN depends on the physical displacement of the optical receiver relative to the LED panel**;
- The results can be improved further by using higher optical power and sensitive receivers;

PULSE AMPLITUDE MODULATION

- Goal:

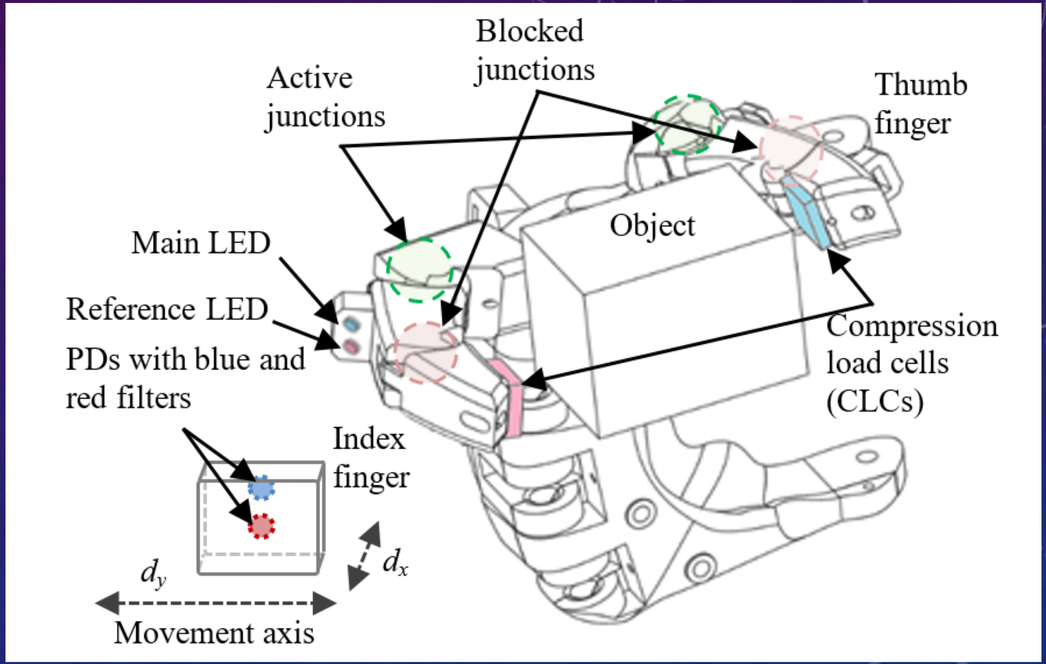
Implement parallel optical links in humanoid robots with motion tolerance

  - From sensors towards the main **SNN** towards actuators
- Existing methods for parallel communication
  - Spatial distribution of the optical channels
    - spatial light modulator, diffractive elements
  - WDM: Costly, limited wavelength resolution, limited spectrum
- Proposed method
  - **Pulse Amplitude Modulation (PAM)** – one wavelength for the main signal
    - **Automatic gain - another wavelength is used for reference**

PROPOSED METHOD – PULSE AMPLITUDE MODULATION

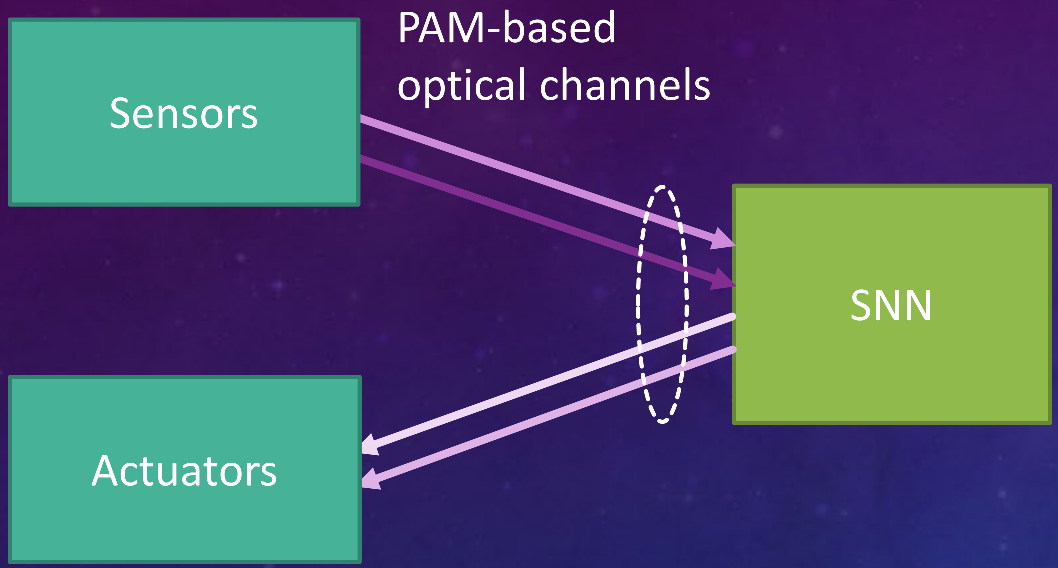
- PAM advantage: the number of channels is determined by:
  - Voltage resolution – limited by the noise
  - Range of the voltage – Theoretically unlimited
- PAM disadvantage:
  - No parallel transmission – **data should be multiplexed in time**
- **Can SNN be tolerant to this disadvantage ?**
- Optical axons generates short optical pulses
- Typically SNN is tolerant to errors in the spike patterns

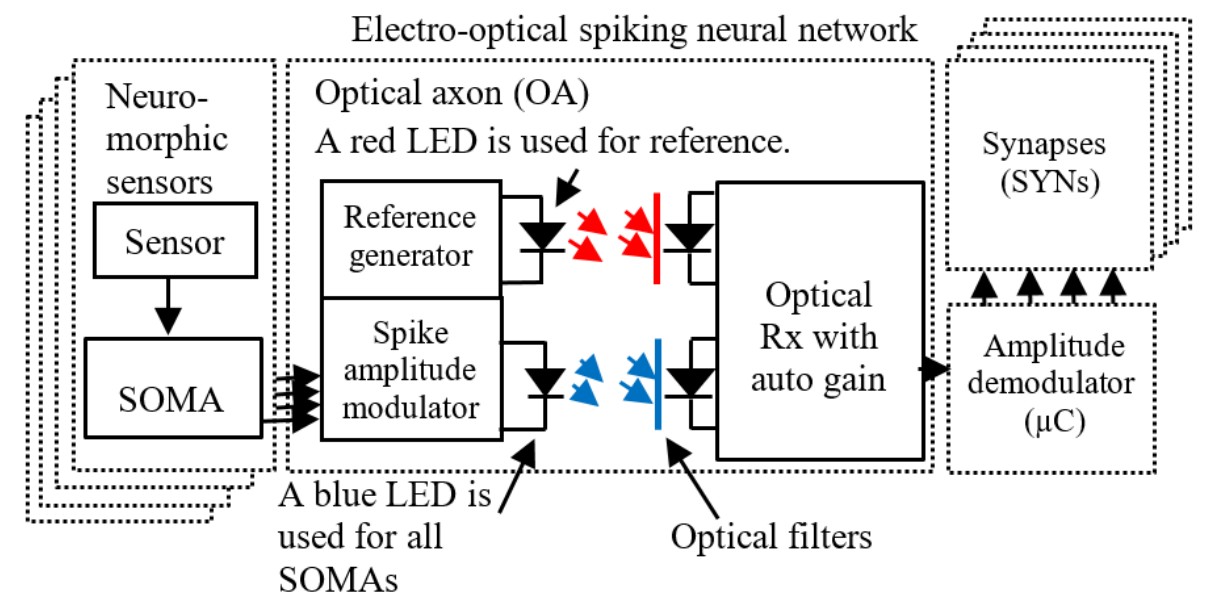
SYSTEM STRUCTURE



- Robotic hand with active index and thumb
- The fingers are actuated by shape memory alloy (SMA);
- The applied force is sensed by neuromorphic sensors placed on the fingertips
  - Compression load cells
- SNN is connected to the fingers through optical channels
- SNN transmits/receives information through the **optical axons**:
  - To the SMA drivers
  - From the neuromorphic sensors

PARALLEL CONNECTIONS BETWEEN NEURONS

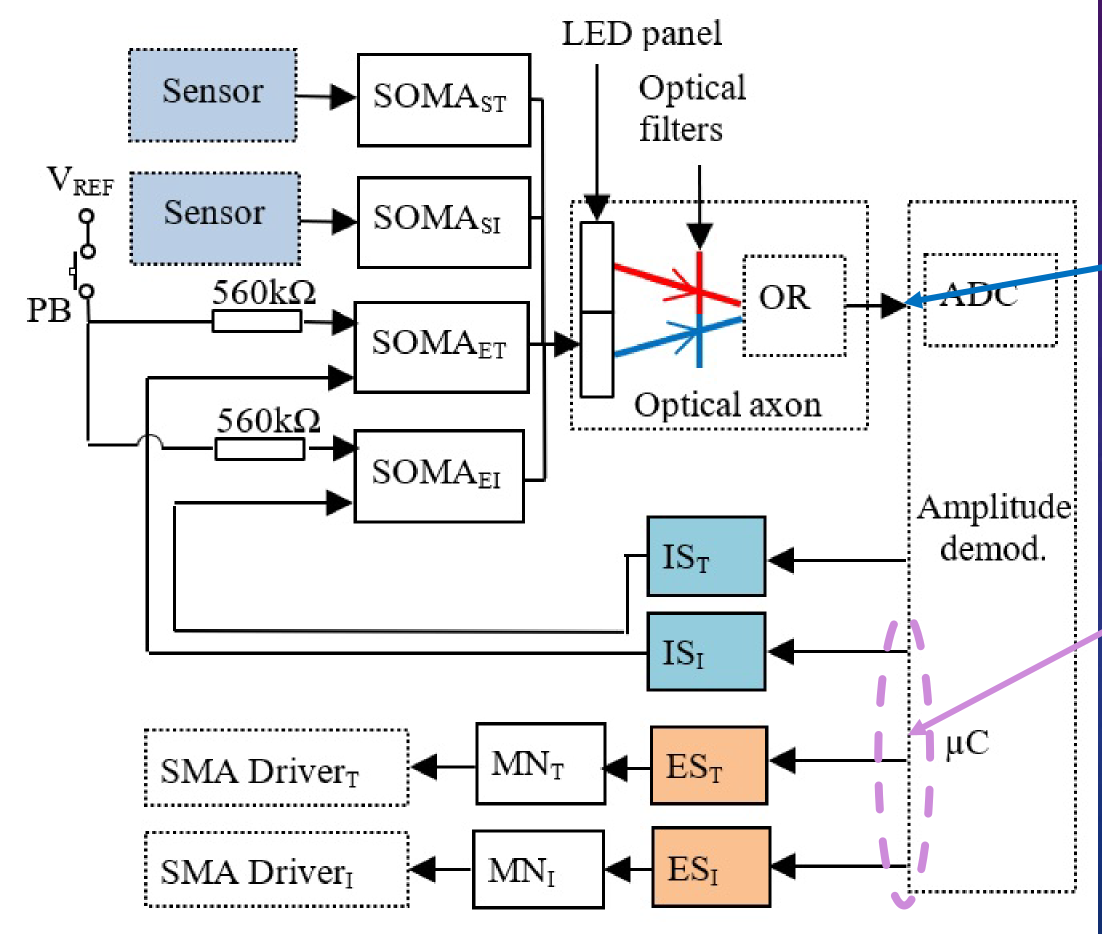




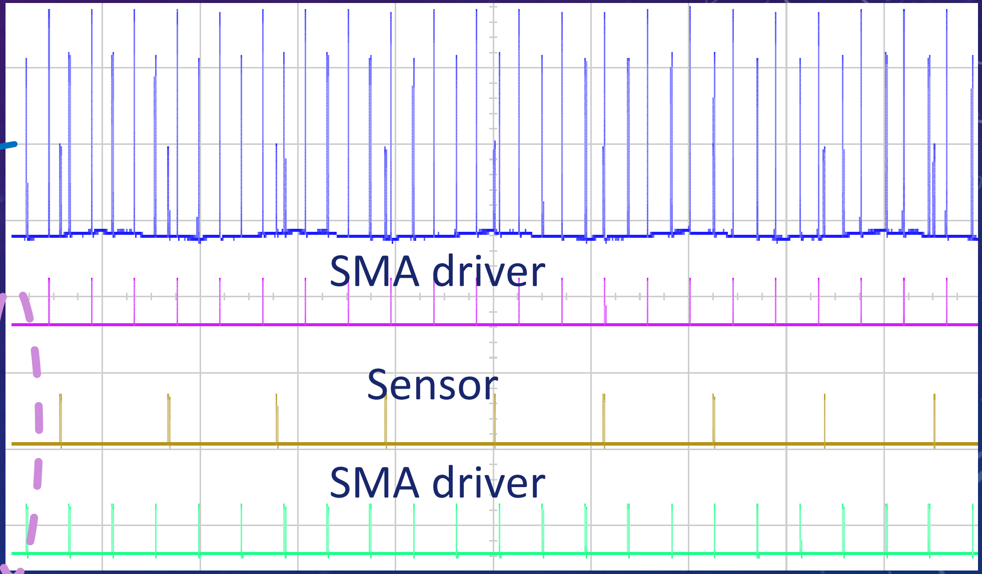
- **Multi Input – optical axon**
  - The synapses are activated by optical pulses.
  - A single LED is powered by all SOMAs
  - Each SOMA drives the LED with a predefined current

OPTICAL AXON WITH PAM

Electro-optical SNN

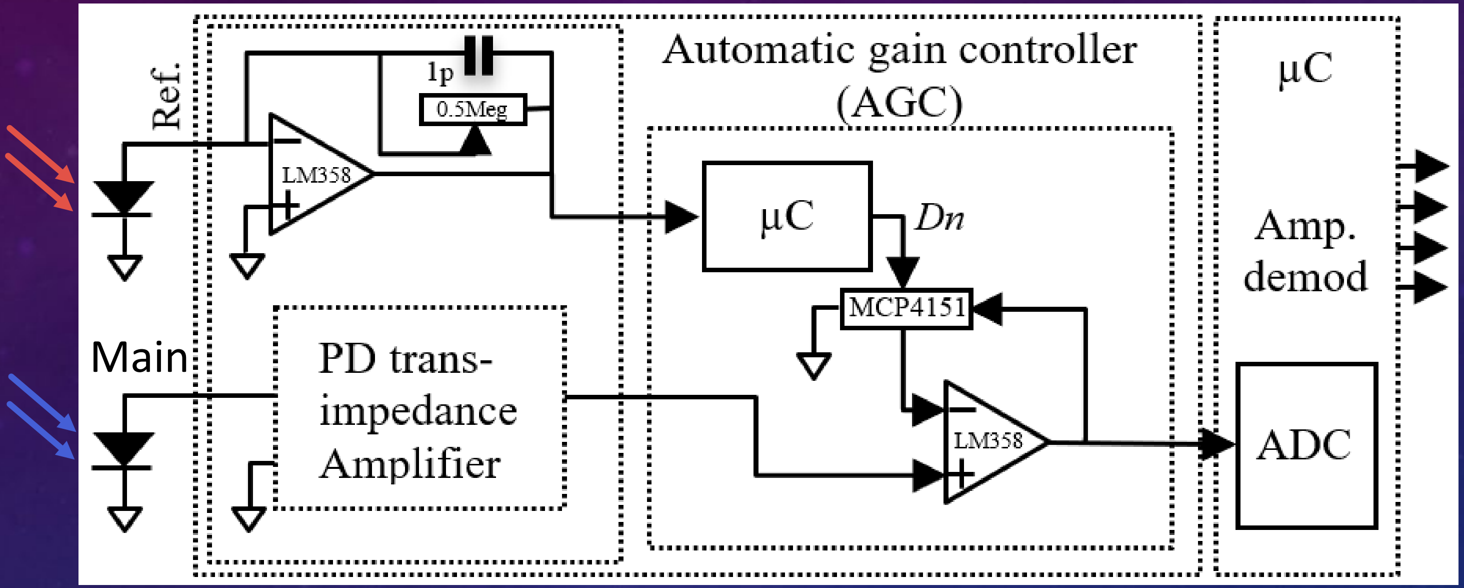


The microcontroller activate the synapses according to the output of the OR



- 4 levels for PAM main signal (blue)
- The gain of OR is adjusted automatically based on the reference signal (red)

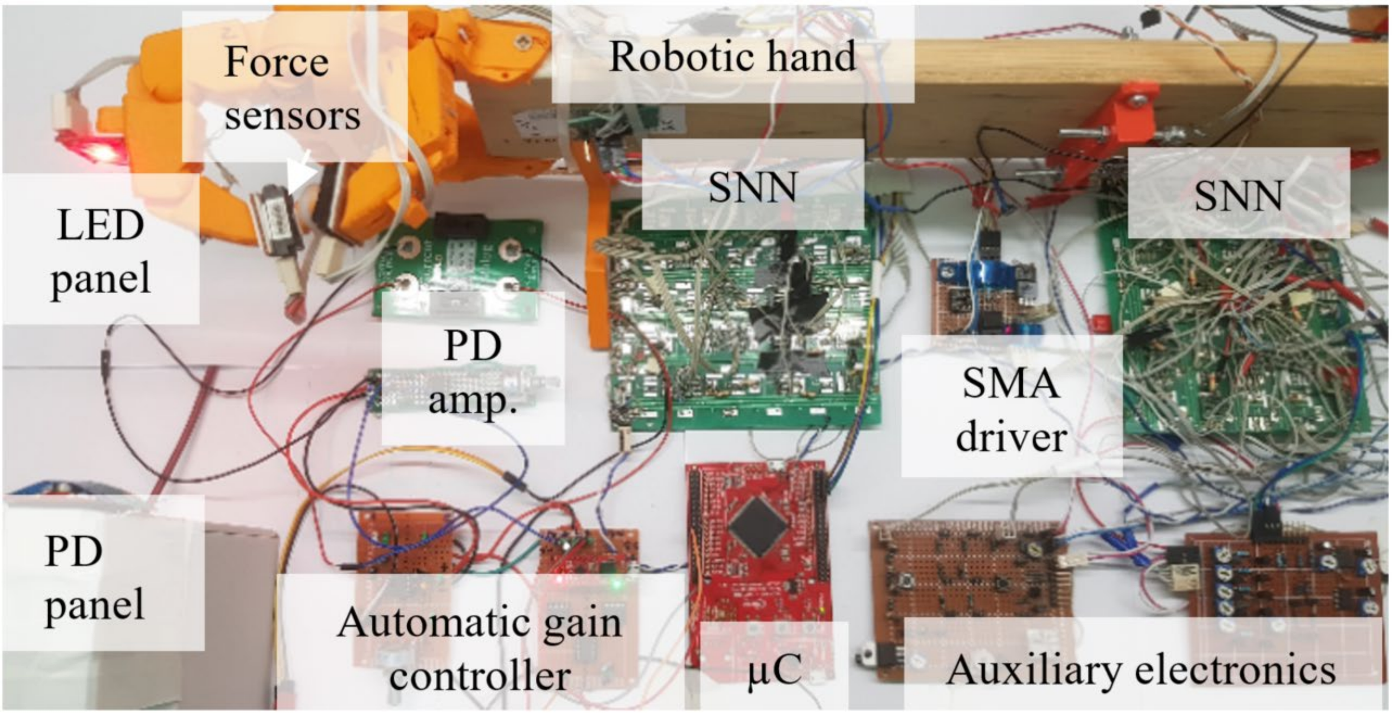
AUTOMATIC GAIN CONTROLLER



- The reference signal (Ref.) is RED while the main signal is BLUE
- The power of reference signal is used to adjust the gain of optical receiver
- Based on (target – read) value of Ref. the Digital POT is programmed

EXPERIMENTAL SETUP

- Evaluate the regulatory performance of the SNN with:
- Hardwired connectivity
- Optical connectivity
- Excitatory neural paths towards actuators
- Inhibitory neural paths from neuromorphic sensors

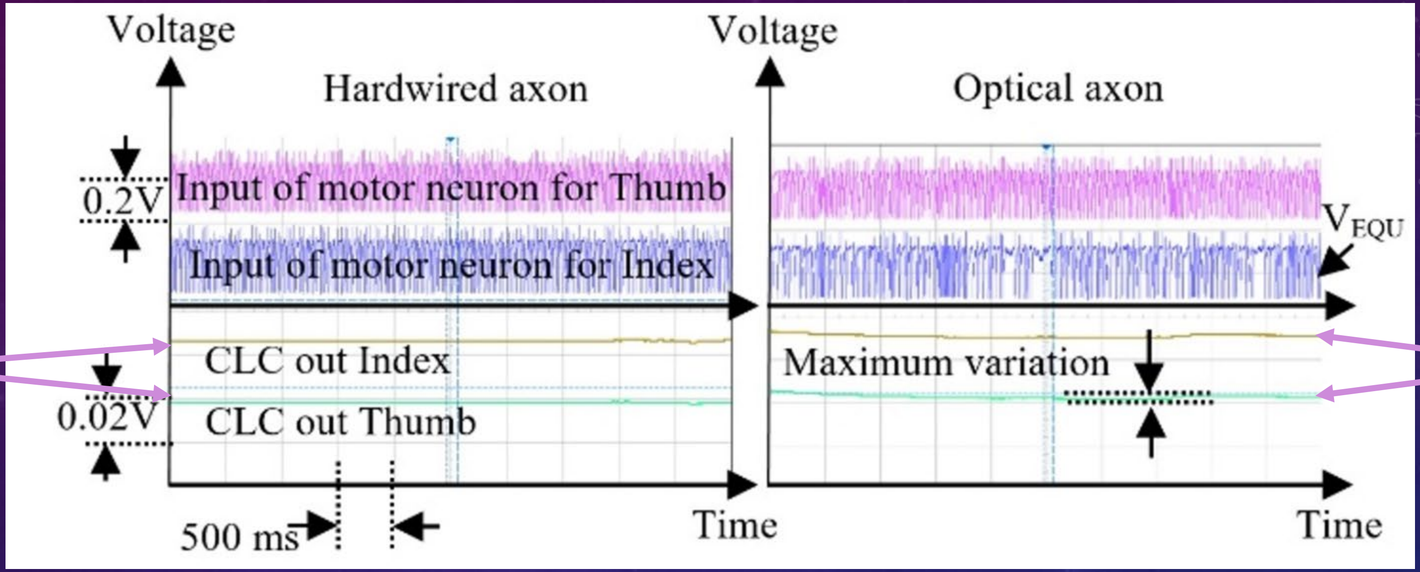


PULSE AMPLITUDE MODULATION

Hardware connection

Line of Sight (OPL = 10 cm)

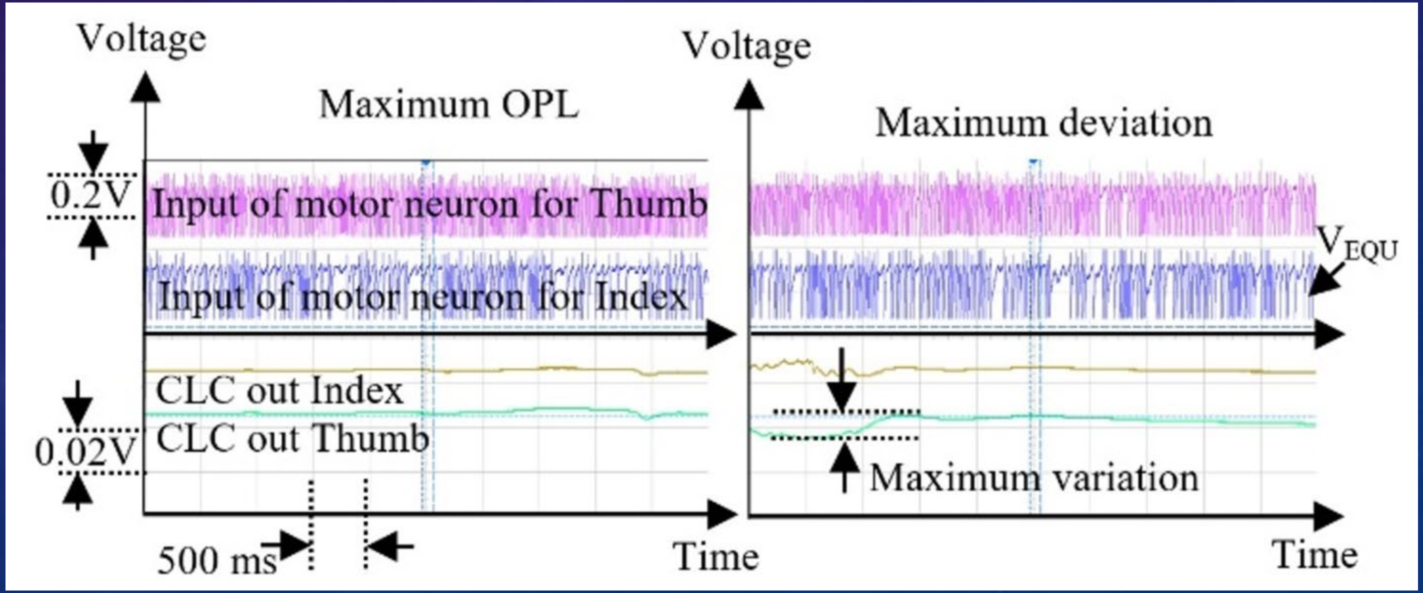
Sensors output



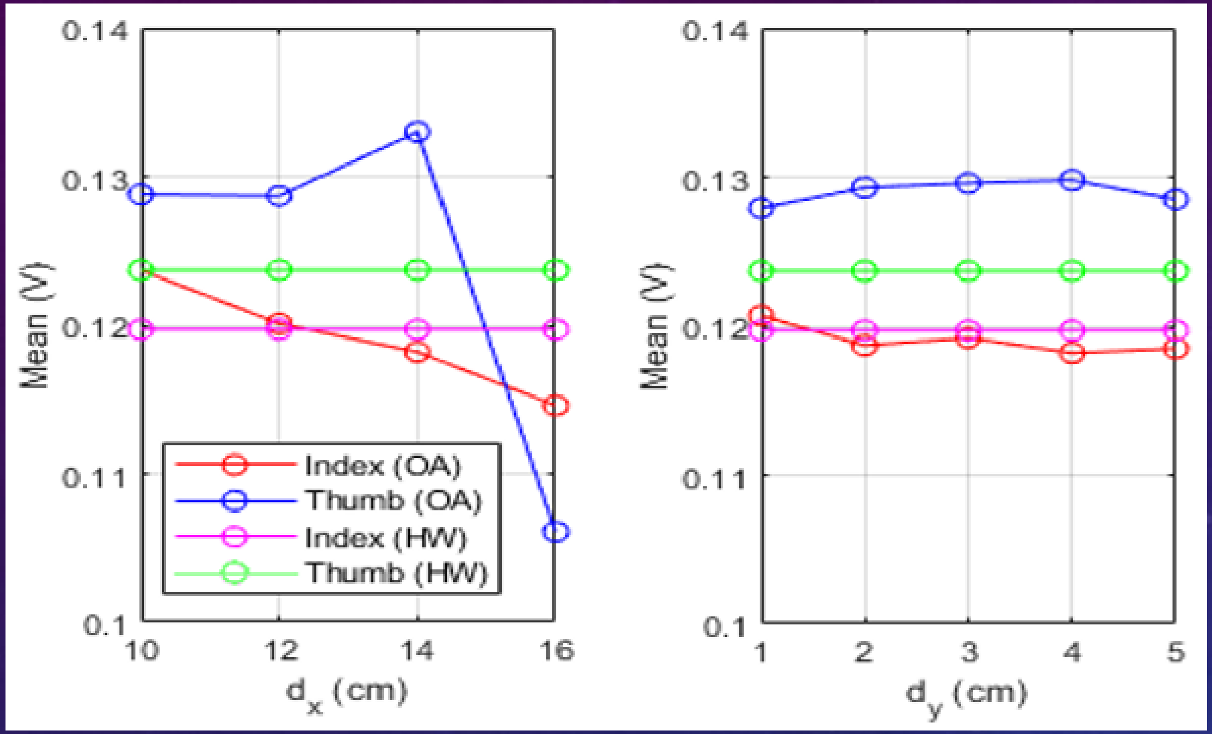
Sensors output

LOS, OPL = dx = 14 cm

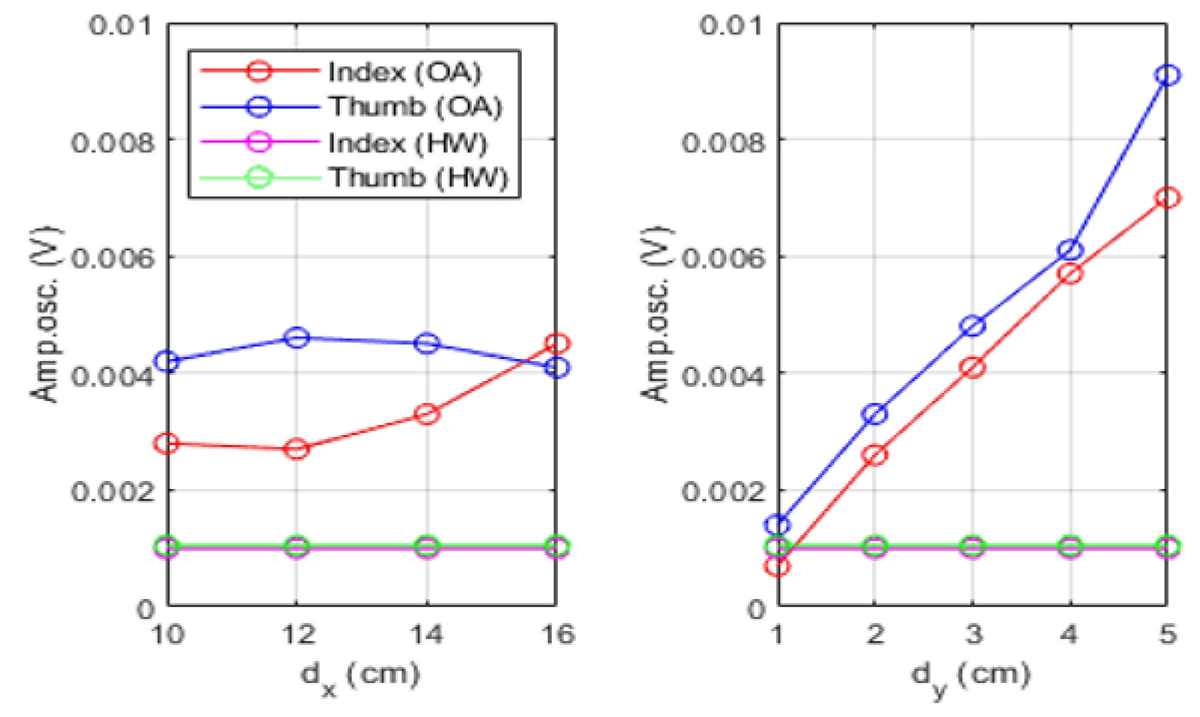
dx = 10 cm; dy = 5 cm displacement



Sensors output is force



Maximum variation



- **The SNN ‘feels’ the presence of optical connections** even for the LOS
- This ‘feeling’ becomes worse with the misalignment
- The hand is able to hold the object despite the use of optical connections

CONCLUSIONS

- **VLC** is an elegant alternative to the hardwired connections which suffers of physical wear.
- PAM reduces the costs and complexity of WDM based systems
- We implemented **Optical axons** with PAM and automatic gain control
- The results demonstrated that **the optical axons affects the regulatory performance of the SNN**
- In this setup the fingers are able to hold an object when the optical channel misalignment varies in certain limits (less then 5 cm)
- **Future work** will compare the WDM and PAM in compensating the effect of channel fading on the SNN activity.

IMPROVEMENTS

On **short term** we will find solutions to:

- To improve the tolerance to the channel length and misalignment (deviation)
- To increase the number of parallel optical channels for electro-optical spiking neural networks
  - The relative timing of spikes is important – the probability of spikes superposition reduces

Long term goals

- The robot’s brain controls its hand through hardwired/optical connections
- The robot’s brain control the hand of other robot through optical conn.
- Evaluates the advantage of OWC between artificial brains.