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Technology to Support PNS Interfaces and Sensorimotor Prosthetic Control: An Engineering Systems Perspective

Intelligent Systems, Robotics and Cybernetics Group
Sandia National Laboratories

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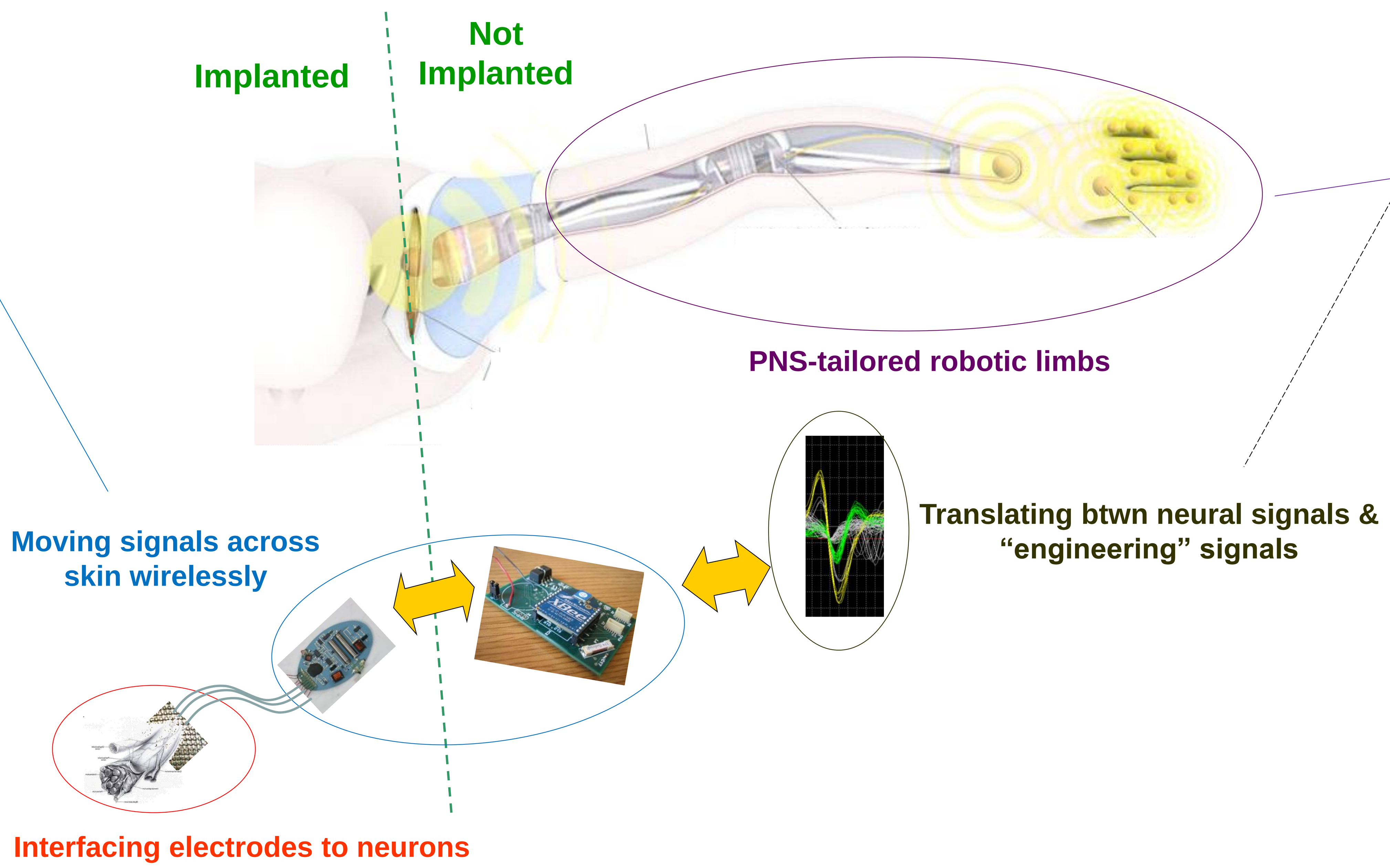


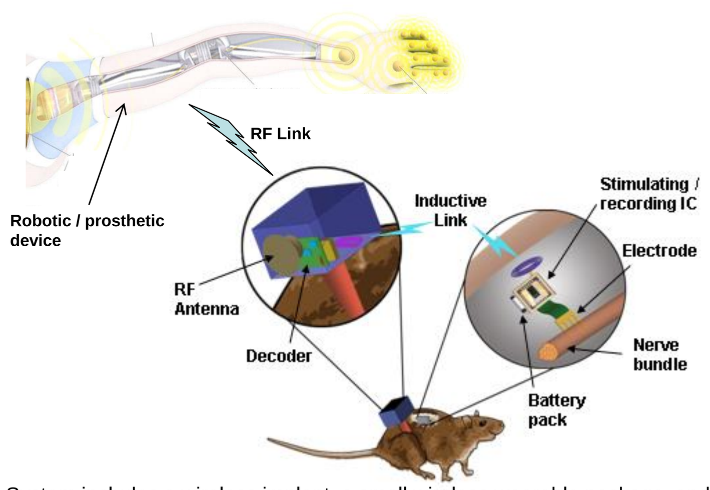
PORTABLE, BIDIRECTIONAL PNS INTERFACE SYSTEM

Sandia: Roy Olsson, PhD; Ken Wojciechowski, PhD, David Novick, PhD; Esteban Yepez; Steve Buerger, PhD; **Collaborators:** University of Michigan; University of Pittsburgh

Project Goal: Demonstrate a fully portable, bidirectional multi-site peripheral nerve interface electronics system with no transcutaneous wires

System Characteristics

- Multi-site neural stimulation and recording
- Flexible, reconfigurable stimulation patterns
- Support potential long-term use (years)
- Physical decomposition:
  - Wireless implanted ASIC-based device
  - Small, low-power, low-voltage wearable device
  - Wireless comms to prosthetic sensors / actuators
  - Separate system to wirelessly charge implanted battery, occasionally (nightly)

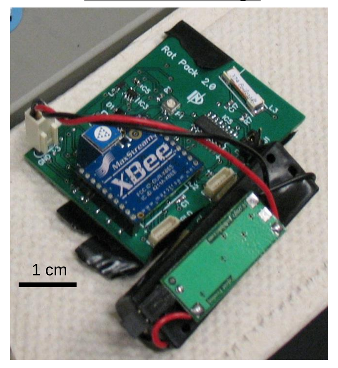


System includes a wireless implant, a small wireless wearable package, and a wireless device including sensors and/or actuators and its own processor

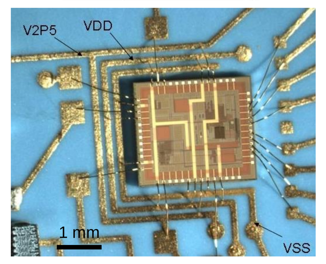
Specifications

- Downlink wireless to implant (stimulation): 33 kbps binary FSK (1 / 2 MHz)
- Uplink wireless (recordings): 200 kbps FSK (8.25 / 10.25 MHz)
- Max separation btwn worn & implanted coils: ~2cm across skin
- Neural stimulation
  - ±35μA @ 2.2μA resolution, 24μs time resolution
  - Up to 8 sites; site impedance ≤ 50 kOhm for full current
- Neural recording
  - 10-bits @ 20 ksps (single site or interleave multiple)
  - Max signal = ±5mA, quantization noise = 1.4μV_{rms}
- Implant battery life / charge: 10h stimulating, 5h recording, 20h idle
- Wearable package:
  - 44 g, ~50 cm^3
  - ~12h charge life per AA battery

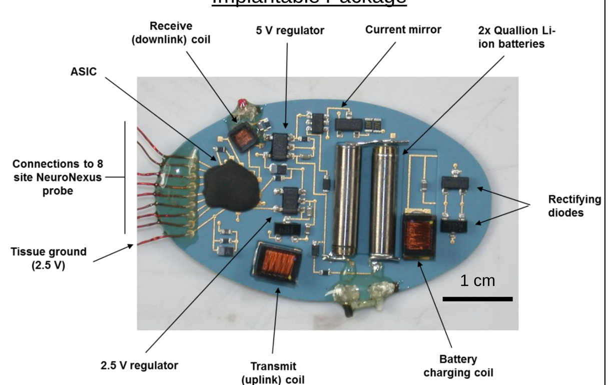
Wearable Package



ASIC (before potting)

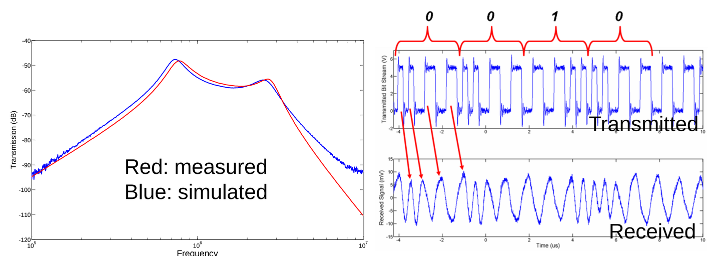


Implantable Package

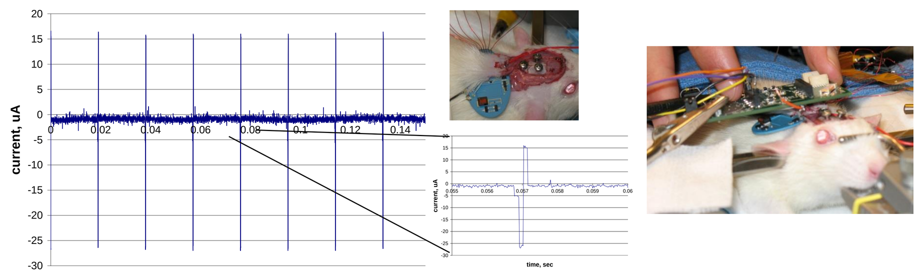


Results and Status

- Gen 1 stimulation path tested in vivo
  - Dual-resonance inductive link, custom FSK protocol validated
  - Controlled stimulation in vitro, in vivo in rat cortex (easier experiment than PNS)

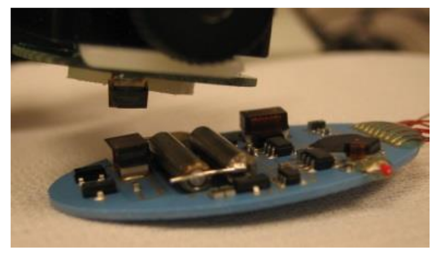


Downlink: Dual resonances at 1 & 2 MHz enable custom, highly robust FSK protocol. Second pulse after each frequency change is used for clocking and decoding to minimize effects of underdamped resonance



Wirelessly commanded stimulation currents measured by pickup electrode in rat motor cortex

- Wireless inductive battery charging validated
  - Tolerates 2-6mm, 50° misalignment at 1cm coil separation
- Gen 2 ASIC designed
  - Reduces implant size by ~50%
    - Power management on chip, reduced # of coils
  - Stimulation waveforms stored on implant; wireless commands trigger pulses



Battery charged inductively from high voltage source

A fully portable, long-term system is feasible

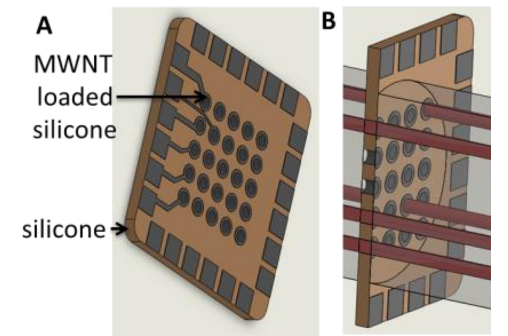
POLYMER COMPOSITE REGENERATIVE PERIPHERAL NERVE INTERFACES

Sandia: Shawn Dirk, PhD; Kirsten Cicotte; Steve Buerger, PhD; **MD Anderson Cancer Center:** Patrick Lin, MD; Gregory Reece, MD; **University of New Mexico:** Elizabeth Hedberg-Dirk, PhD

Project Goal: Explore porous composite polymer material systems for regenerative PNS interfaces

Concept

- Elastomeric mat with selectively patterned conductive filler (e.g. MWCNTs)
- Porous structure to support axonal through-growth
- Match elastic modulus of composite to nerves for health as nerve regrows

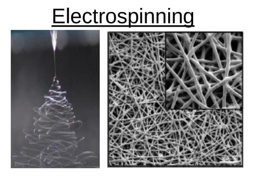


Concept: **A** Thin porous mat with conductive regions around pores, conductive traces and connection pads. **B** Axon bundles growing through pores

Animal Model

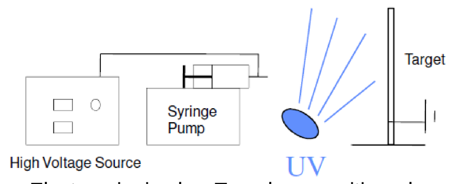
- Implanted in hind limb peroneal nerve of Sprague-Dawley rats using microsurgical techniques
- Evaluated ingrowth and health after 3 wks

Electrospinning

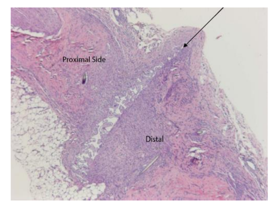


Fabrication Method #1: Electrospinning PDMS

- High voltage field applied between pump tip and collection plate
- Novel method: Photo-crosslink while spinning low Tg polymers
- Animal results: Limited axonal ingrowth: pores too small



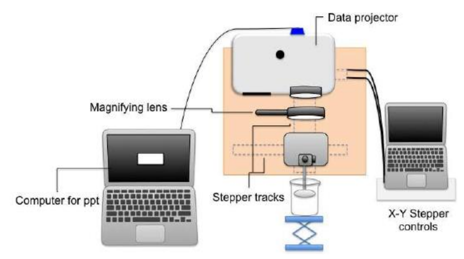
Electrospinning low Tg polymers with real-time photo-crosslinking



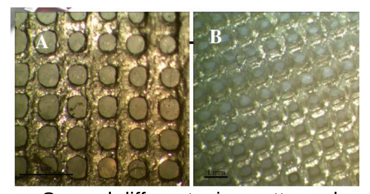
Histology: No axonal ingrowth after 3 weeks

Fabrication Method #2: Projection Microstereolithography

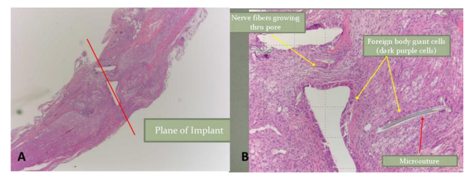
- Layered development with micron sized features using inexpensive projector, converging optics
- Precisely patterned hole arrays
- Pure PDMS: Healthy axonal ingrowth with ~200 μm holes
- MWCNT loaded PDMS: Caused inflammatory response
- Next steps: need coating or alternative nanoparticles



Laboratory Projection Microstereolithography setup



Several different micropatterned PDMS arrays



Histology (Left: low mag; Right: high mag): Pure PDMS mat. Significant axonal ingrowth through 200 um hole. Minimal immune response similar to that near nylon suture.

Material Properties

- Elastic Modulus: Tunable to hundreds of kPa (nerves ~500 kPa)
- Conductivity: Matches Au at low freqs; within 10x of gold @ 1 kHz

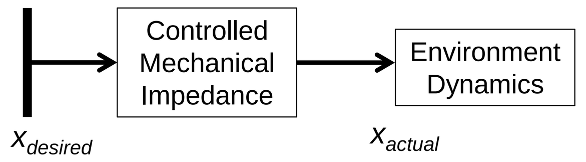
Lithography is a viable means of forming regenerative interface electrodes; need appropriate conductive filler

PNS-CONTROLLED ROBOTIC LIMBS FOR RICH PHYSICAL INTERACTION

Assertion: To realize their full potential, PNS-controlled prosthetics must be tailored to match the unique characteristics of their control

Models for manipulation

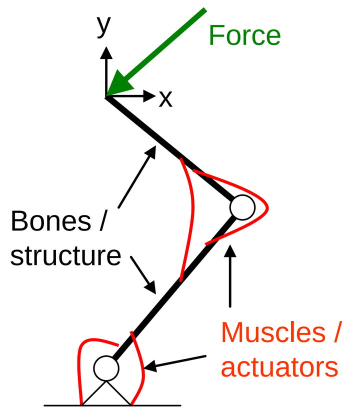
- Motion control
- Force / torque control
- Impedance / interaction control
  - Modulate desired force OR motion AND mechanical impedance (dynamic stiffness)
  - Energetic interaction with wide range of environment dynamics (e.g. pushing heavy cart, digging with shovel, playing piano)



Schematic of impedance control. Desired motion and impedance are specified. Manipulator and environment dynamics influence actual achieved motion

PNS vs. cortical prosthetic limb control

- Cortical: Control based on motion intention
  - Primarily motion control
- Peripheral: Control based on muscle activation
  - Muscle activation can modulate impedance as well as force
  - E.g. agonist / antagonist muscle co-contraction



Robot / actuator characteristics required for effective interaction control

- Sensory feedback to control system
- High force, low mass actuators with low and variable mechanical impedance
  - Traditional highly geared systems are ill-suited
- Appropriate control system structure to explicitly regulate impedance

Sensorimotor interfaces to the PNS provide key characteristics necessary for high-performing interaction control. Appropriate prosthetic design and control will be required to take advantage.

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