Neuromorphic Computation for Autonomous Mobility in Natural Environments

Rolf Müller, Ruihao Wang, Omar Khyam,
David Alexandre, Ananya Bhardwaj
rolf.mueller@vt.edu

Department of Mechanical Engineering, Virginia Tech

March 28th, 2019

Autonomy for the Real World

source: *random web find*

Autonomy for the Real World

WSPY News.com photo by Doug Nelson

Bats as a Model

photos: D. Nill

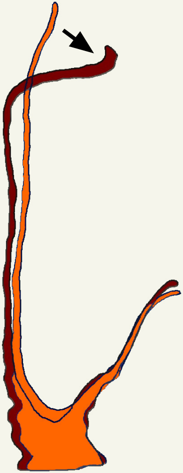
Complexity of Bat Habitats

Peripheral Dynamics

Components of Peripheral Dynamics

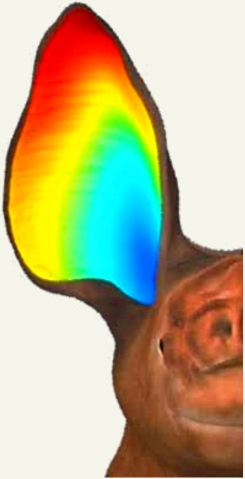
reorientation

non-rigid deformation



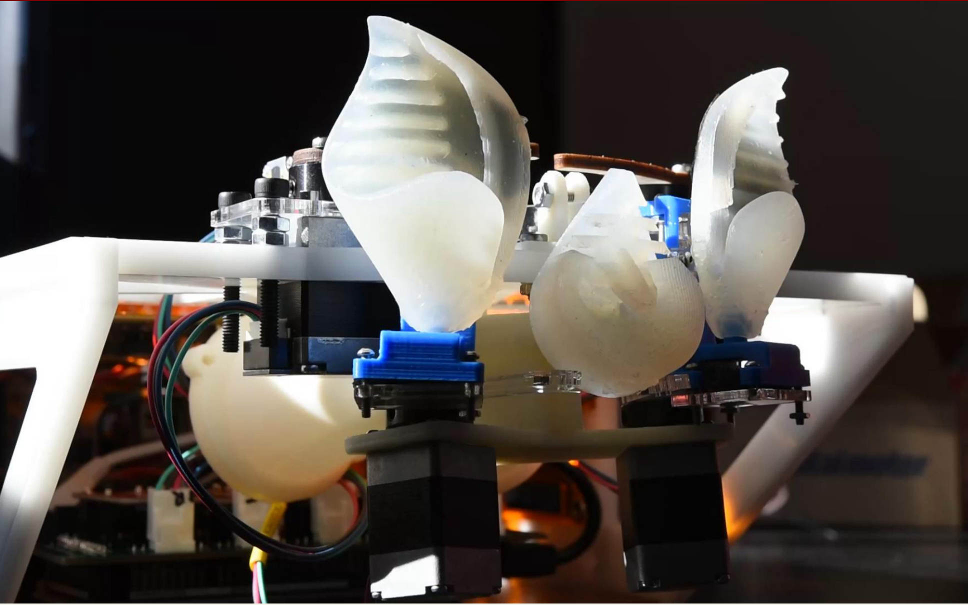
Gao & Müller
Phys. Rev. Lett.
(2011)

nonlinear transform

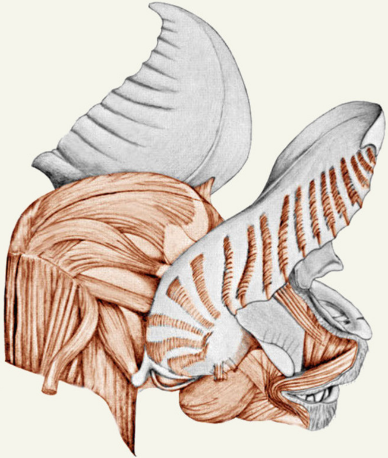


Yin & Müller
Proc. Natl. Acad. Sci. USA
(under revision)

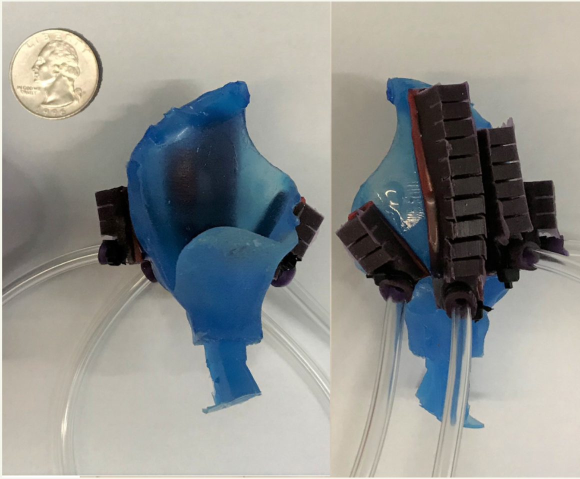
Dynamic Biomimetic Sonar Head



Softrobotic Reproductions

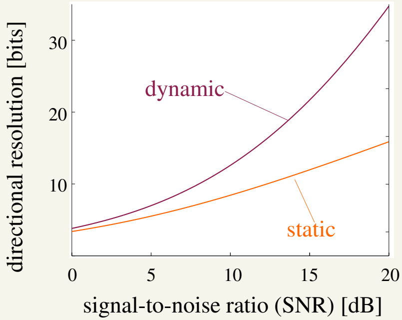


Schneider & Möhres, Z. Vergl. Physiol. (1960)

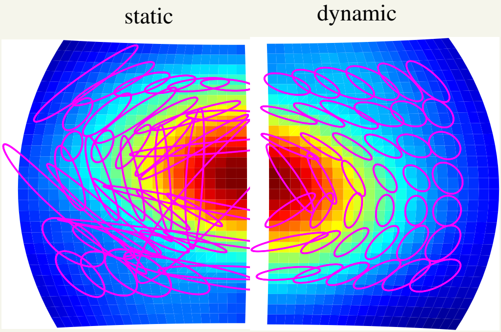


Eckman, Müller, et al., J. Acoust. Soc. Am (in press)

Performance Gain Example: Direction Finding

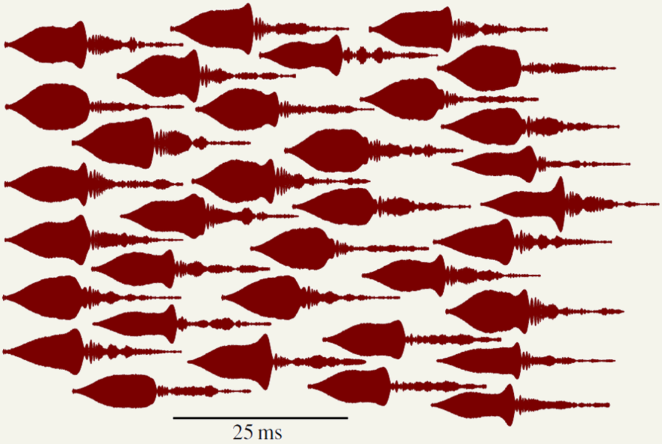


Müller et al., Phys. Rev. Lett. (2017)



Gilani & Müller, J. Acoust. Soc. Am. (2016)

Natural Stimulus Ensemble



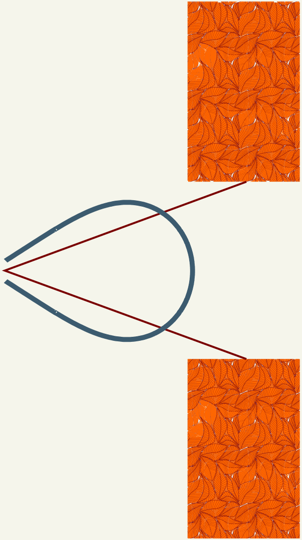
- 4 different field sites
- 220,000+ uncorrelated echoes

Real-World Task: Finding Passageways in Foliage

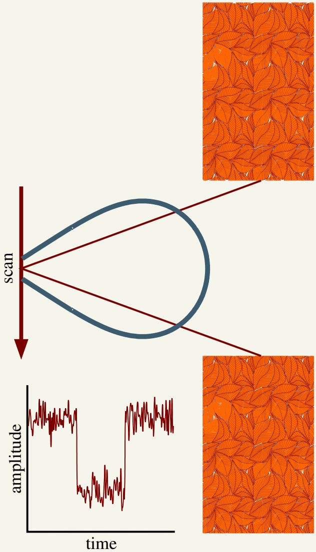
- Foliage size: 1.5 x 1 x 0.8 m (LxHxW)
- Gap widths: 10, 20, 30 cm
- Distances: 0.6 – 1.4 m
- Number of echoes: 12,000

VIRGINIA TECH

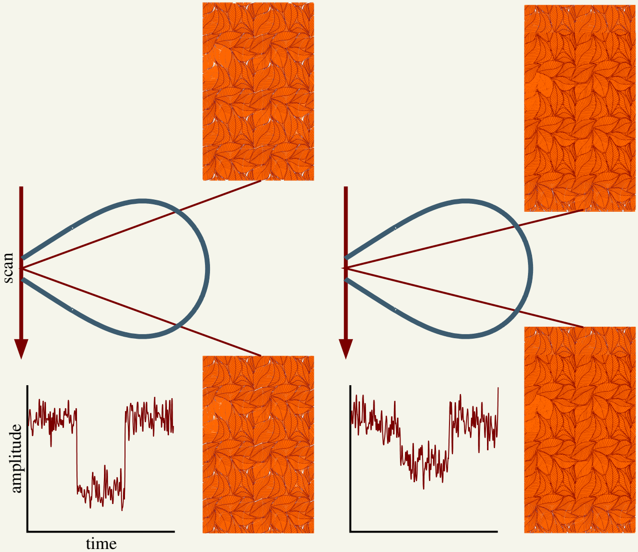
Real-World Task: Finding Passageways in Foliage



Real-World Task: Finding Passageways in Foliage

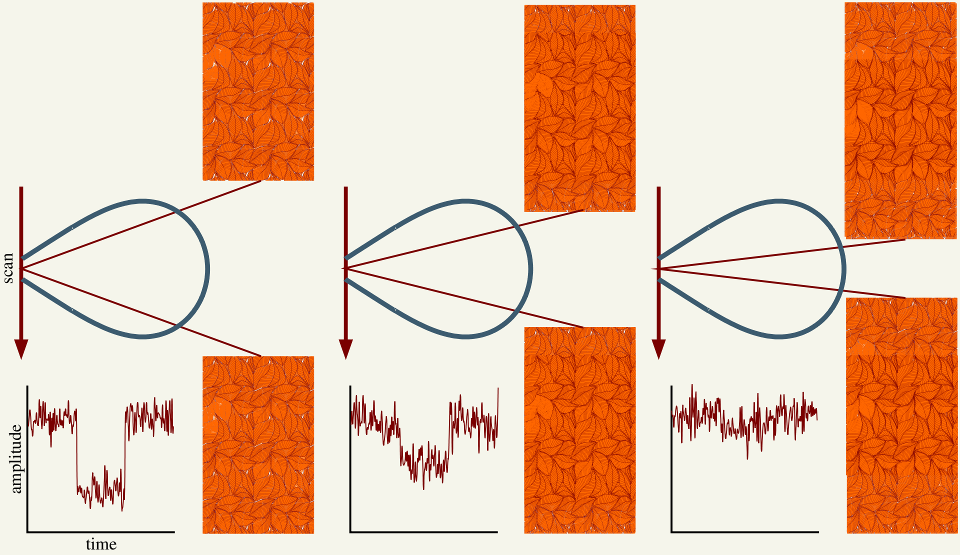


Real-World Task: Finding Passageways in Foliage



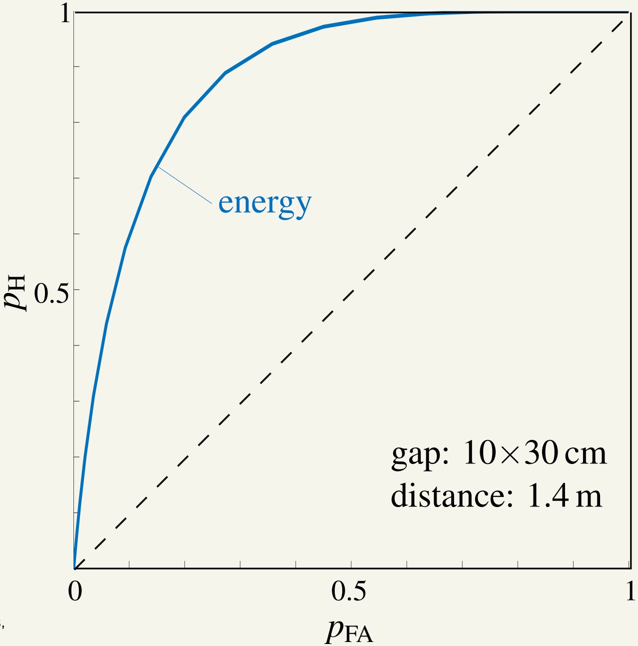
VIRGINIA TECH

Real-World Task: Finding Passageways in Foliage

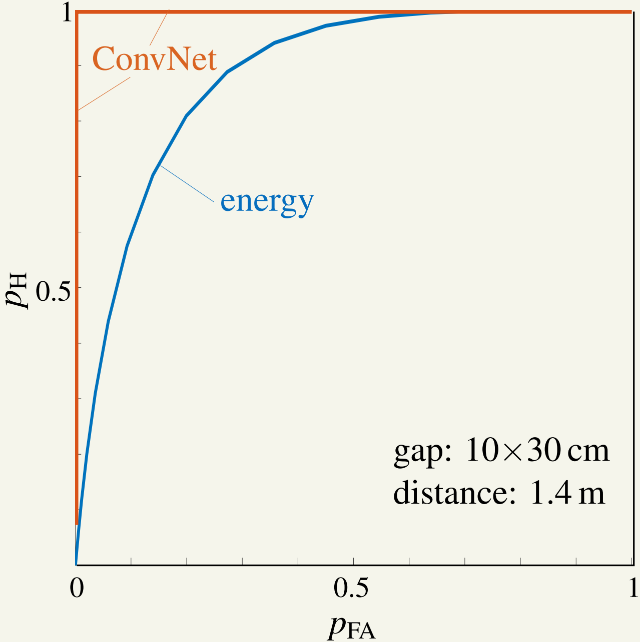


VIRGINIA TECH

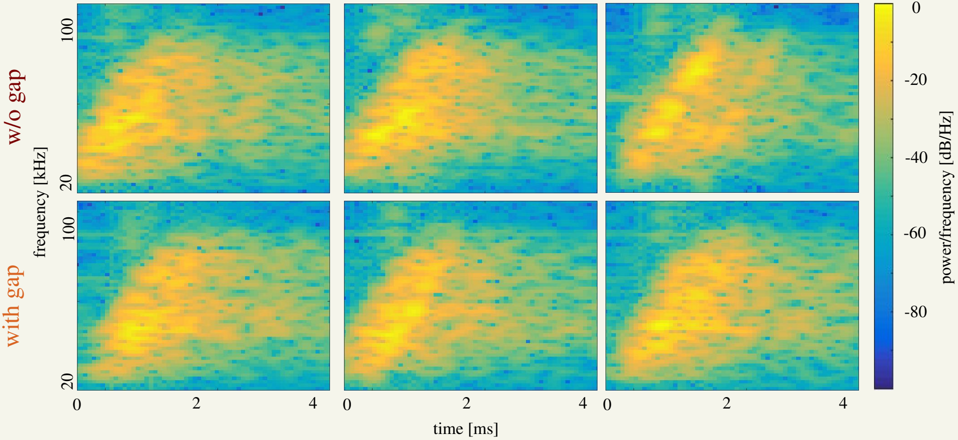
Real-World Task: Finding Passageways



Real-World Task: Finding Passageways



Real-World Task: Finding Passageways



R. Wang & R. Müller, J. Acoust. Soc. Am. (2018)

1. time variance encodes sensory information
   $\rightarrow$ timing matters

Dynamic Biosonar & (Spiking) Neuromorphic Computing

1. time variance encodes sensory information
   $\rightarrow$ timing matters

2. short time scales (1 - 50 ms)
   $\rightarrow$ computation based on a few spike times

Dynamic Biosonar & (Spiking) Neuromorphic Computing

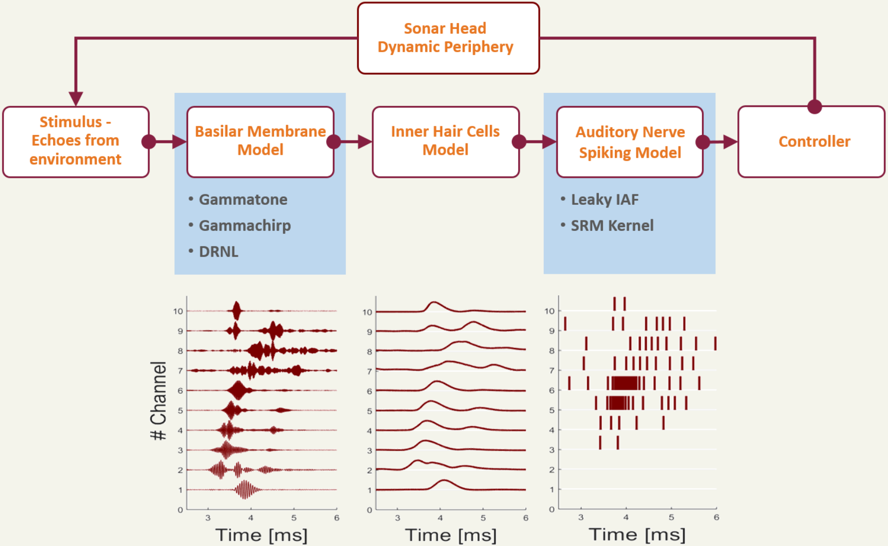
1. time variance encodes sensory information
   $\rightarrow$ timing matters
2. short time scales (1 - 50 ms)
   $\rightarrow$ computation based on a few spike times
3. fast (<100 ms) closed-loop control
   $\rightarrow$ hardware implementation

Dynamic Biosonar & (Spiking) Neuromorphic Computing

1. time variance encodes sensory information
   $\rightarrow$ timing matters
2. short time scales (1 - 50 ms)
   $\rightarrow$ computation based on a few spike times
3. fast (<100 ms) closed-loop control
   $\rightarrow$ hardware implementation
4. pilot data ...

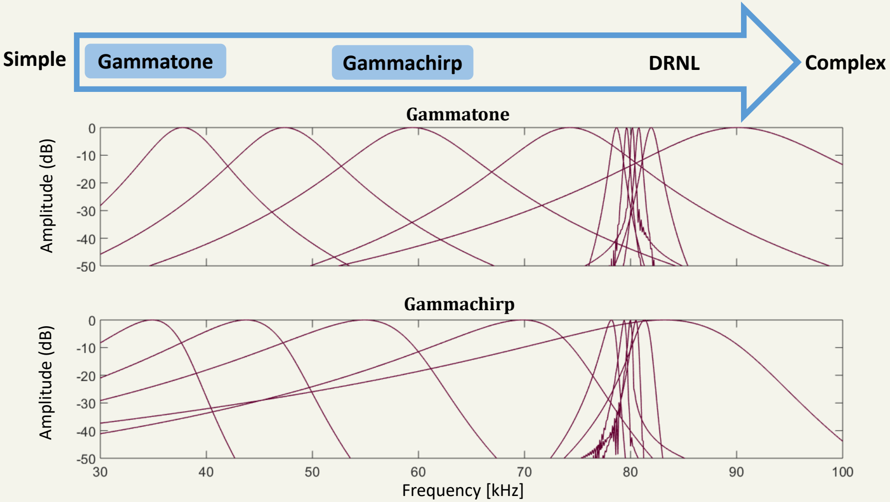
VIRGINIA TECH

Neuromorphic Signal Representations

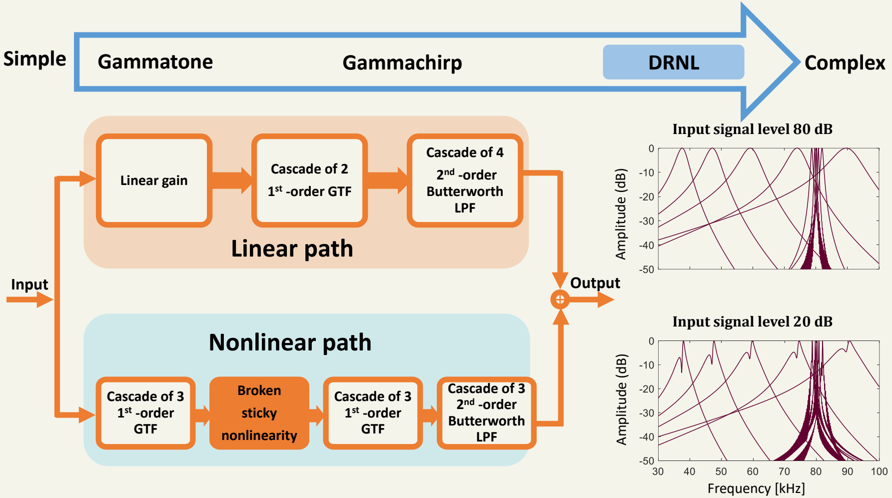


VIRGINIA TECH

Linear Models: Symmetric vs. Asymmetric

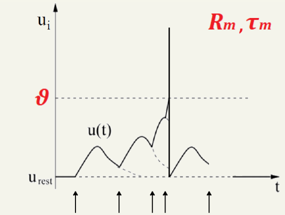


Dual-Resonance Nonlinear (DRNL) Model

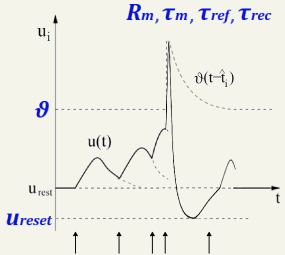


Spike Response Models

- **Leaky Integrate-And-Fire:**
  - simple integration
  - static threshold
  - **3 parameters**



- **Response Kernels:**
  - after-potential computation
  - reduced responsiveness after spike
  - dynamic threshold
  - **6 parameters**



VIRGINIA TECH

Optimization of Model Parameters

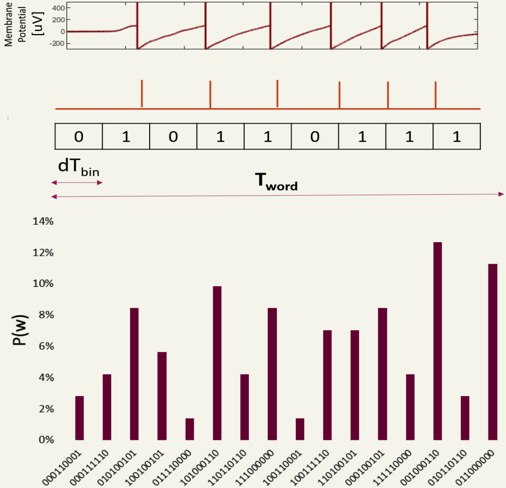
- optimization over entire parameter space
- objective: static/dynamic difference in coding capacity
- information-theoretic analysis (entropy)

Information-Theoretic Analysis: Direct Entropy Method

Binning

Plug in PDF

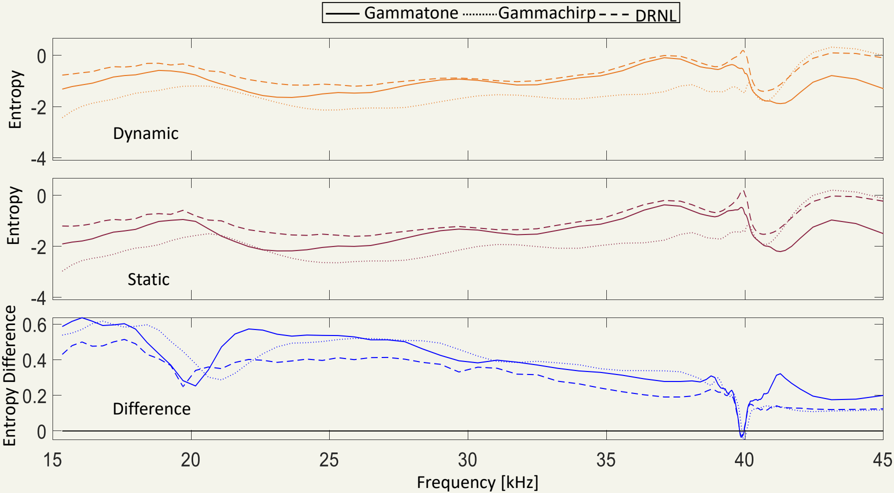
Entropy



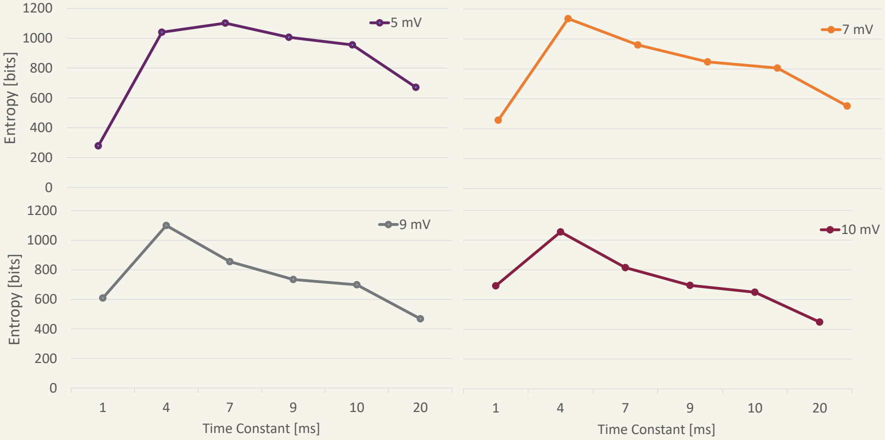
$$H(w) = -\sum P(w_i) \cdot \log_2 P(w_i)$$

VIRGINIA TECH

Peripheral Dynamics & Primary Signal Representation



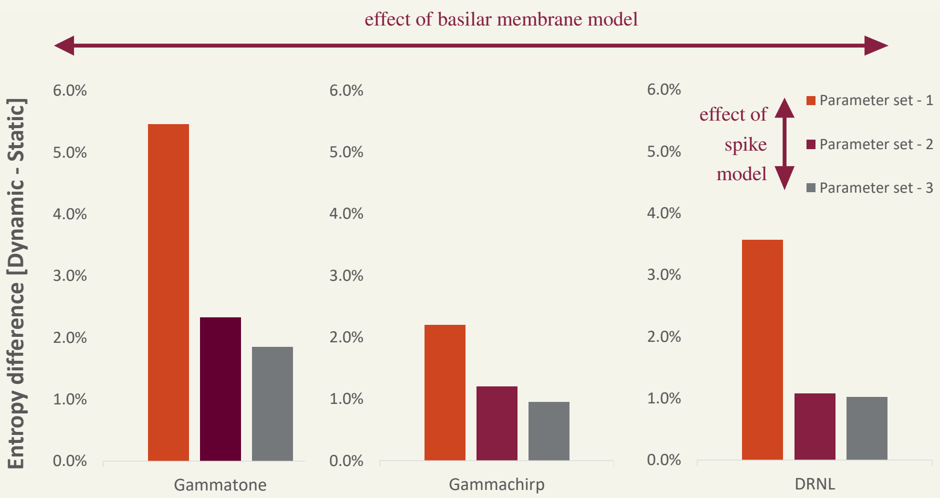
Peripheral Dynamics & Neural Coding Capacity



LIAF spike model

VIRGINIA TECH

Peripheral Dynamics & Neural Coding Capacity



response kernel spike model

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
    1. peripheral information encoding
    2. primary signal representation

VIRGINIA TECH.

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control
- pilot data: coding capacity depends integration of peripheral dynamics, primary representation, & neural model

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control
- pilot data: coding capacity depends integration of peripheral dynamics, primary representation, & neural model
- future work:

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control
- pilot data: coding capacity depends integration of peripheral dynamics, primary representation, & neural model
- future work:
  - useful information

VIRGINIA TECH.

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control
- pilot data: coding capacity depends integration of peripheral dynamics, primary representation, & neural model
- future work:
  - useful information
  - better neuromorphic computing (paradigms & hardware)

Summary: Bats, Bushes, & Brains

- autonomy in complex natural environment is possible
- hypothetical key components:
  1. peripheral information encoding
  2. primary signal representation
  3. neuromorphic signal representation & computing
  4. system integration & adaptive control
- pilot data: coding capacity depends integration of peripheral dynamics, primary representation, & neural model
- future work:
  - useful information
  - better neuromorphic computing (paradigms & hardware)
  - adaptive control

Acknowledgments

ONR *"MURI: Bioinspired Adaptive Sonar for Classification and Guidance in Complex Environments"*

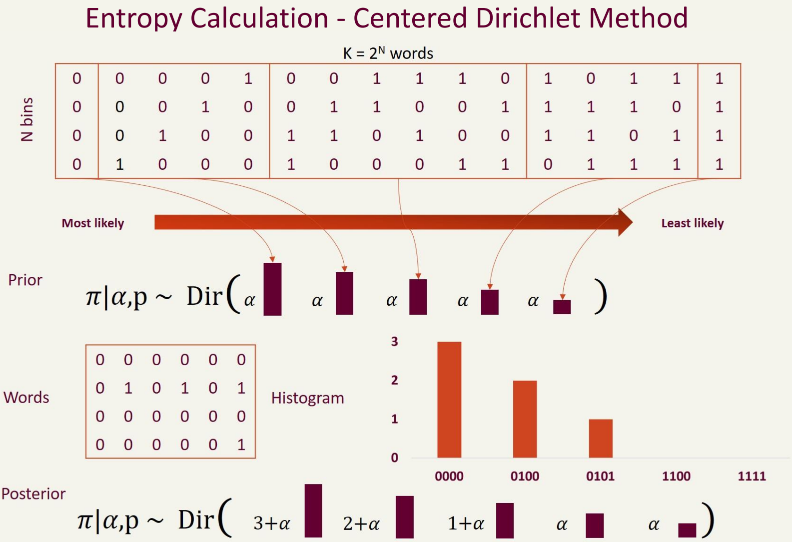
NAVSEA/NEEC *"Bioinspired Broadband Sonar"*

NSF *"Novel Dynamic Paradigms for Wave-based Sensing"*

IBM Faculty Award

VIRGINIA TECH.

Information-Theoretic Analysis: CDM Entropy Method



Peripheral Dynamics & Neural Coding Capacity