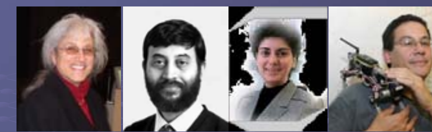
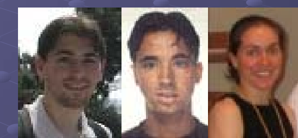
Generation and Control of Spinal Locomotion Signals and Their Application to Biomorphic Robots

Ralph Etienne-Cummings
Dept. of Electrical and Computer Engineering
Johns Hopkins University



Avis H. Cohen (UMCP), Nitish V. Thakor (JHU), Vivian K. Mushahwar (UA), M. A. Lewis (Iguana Robotics)



Jacob Vogelstein (JHU), Francesco Tenore (JHU), Lisa Guevremont (UA), Alex Russel (UCT), Garrick Orchard (UCT)

Sponsors:
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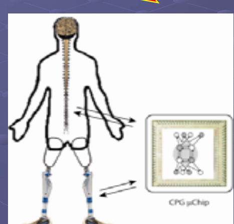
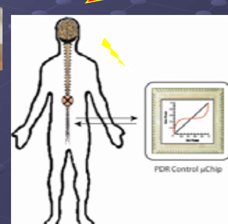
The Big Picture: Motivation

Developing Biomorphic Robotics



Restoring function after limb amputation

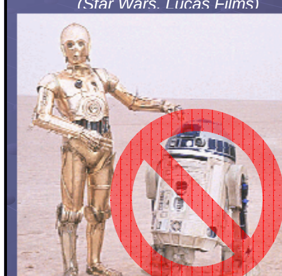
Adaptive Biomorphic Circuits & Systems



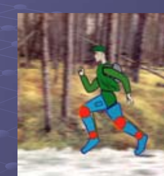
Restoring locomotion after severe spinal cord injury

Motivation

(Star Wars, Lucas Films)

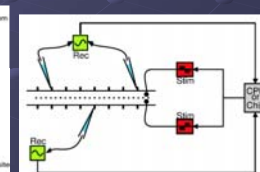


Humanoid (Legged) Robotics



Physical Augmentation (Iguana Robotics)

Cleveland FES Center, Case-Western Reserve U.



Prosthetic Devices

REVOLUTIONARY PROSTHETICS

DARPA Funded

Presentation Outline

- Introduction
  - Central pattern generators
  - Spinal cord injury
  - Proposed locomotion controller
- Experiments & results
  - Model systems
  - Gait controller: *in vivo* results
  - Phase controller: *in vitro* results
- Ongoing and future research
  - Adaptation and Learning: *in roboto*
- Conclusion

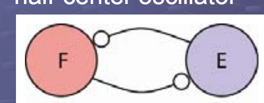
Central Pattern Generator (CPG)

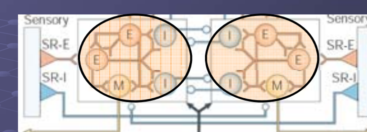
- Networks of neurons in the spinal cord of vertebrates
- Generate sequences of patterned outputs to activate muscles
- Control motor systems with regular, periodic activity (breathing, chewing, locomotion, etc.)
- Basic architecture is preserved across species [Cohen et al., 1988]
- Basis of locomotion in all vertebrates studied to-date, including primates and humans*
  - Convincing evidence in marmosets [Fedirchuk et al., 1998]
  - Similar data in humans (without deafferentation) [Dimitrijevic et al., 1998]
- CPG is used for "*periodic*" not specialized, locomotion

Source: J. M. Cleese, MPFC, 1970

CPG Architecture

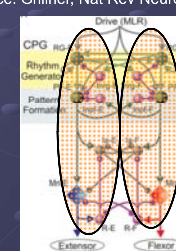
- First conceptual "model" in 1911 by T. G. Brown: half-center oscillator





Source: Grillner, Nat Rev Neurosci, 2003

- HCO structure preserved in modern models
- Cellular models in primitive vertebrates
- Models in higher vertebrates are less detailed; designed to match behavioral data

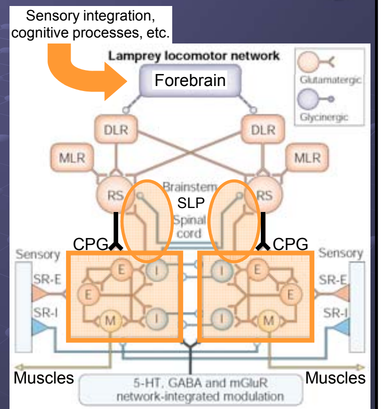


Source: Rybak et al., J Physiol, 2006

Locomotor Control Loop

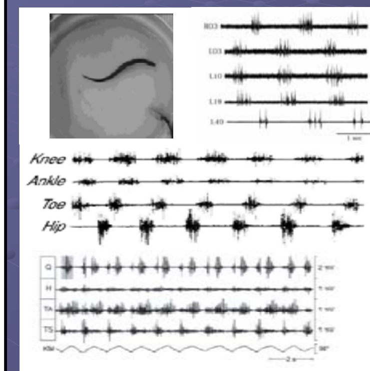
- Forebrain selects motor program, aka "gait" (e.g. walk, run, speed, etc.)
  - Forebrain communicates gait info to brainstem (MLR/DLR)
  - Brainstem uses tonic descending inputs to activate CPG and configure it for gait [Matsuyama et al., 2004]
- CPG generates motor pattern, activates motor neurons, initiates movement
- Feedback from CPG produces efferent copy in brain [Dubuc & Grillner, 1989]
  - Online measure of spinal cord activity
  - Compare current to desired output
- Armed with efferent copy, brain and brainstem use phasic (precisely-timed) inputs to modulate CPG activity [Deliagina et al., 2002]
  - Manipulate individual components of motor output
  - Produce specific motor pattern (e.g. turning)
  - Correct errors or adapt to environment
- Continuous feedback loop essential for controlling and adapting locomotion

forebrain → brainstem → CPG → limbs
brainstem ← CPG



Source: Grillner, Nat Rev Neurosci, 2003

CPGs in Action



Source: Mellen et al., 1995;
Grillner & Zangger, 1984; Minassian et al., 2004

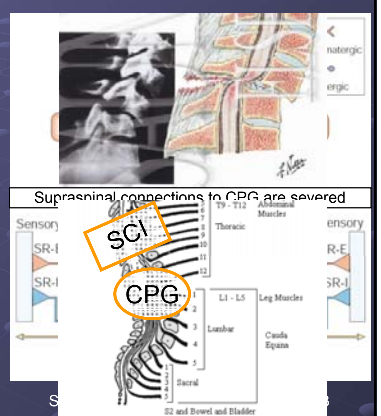
Spinal Transection @ T11

- The CPG is self-sufficient and contained within the spinal cord

Spinal Cord Injury (SCI)

- SCI is usually a focal injury: vertebral body dislocation → spinal cord contusion
  - Kills spinal cord cells at lesion site
  - Severs connections
  - Leaves cells above/below lesion intact
- In most cases (~65%), lower limb CPG is intact after SCI
- Paralysis is caused by loss of descending control of the CPG, not by loss of CPG itself
  - Tonic & phasic inputs to CPG are disconnected
  - Efferent inputs required to activate CPG and control locomotion

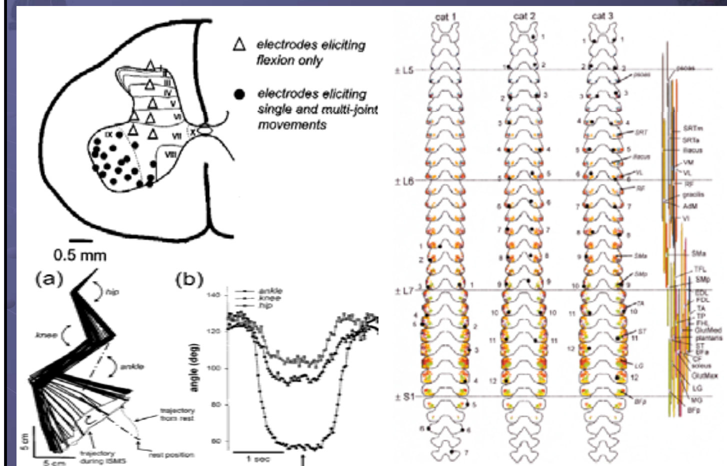
→ Paralysis



How to Restore Locomotion

- Historically, locomotor prostheses have ignored the CPG after SCI and activated muscles directly through functional electrical stimulation (FES) of peripheral motor axons (PMA)
- Advantages
  - ☺ Simple in concept: one electrode per muscle
  - ☺ It kinda works: elicits strong contractions
- Disadvantages
  - ☹ Requires a lot of power (mA per contraction)
  - ☹ Requires a lot of (distributed) electrodes
  - ☹ PMA stimulation causes reverse muscle recruitment
    - Rapid fatigue (avg. range 300m [Klose et al., 1997])
    - Inelegant, jerky movements (poor synergies)
- Alternative: intraspinal microstimulation (ISMS)

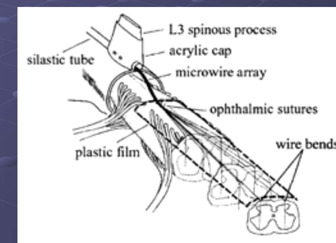
Intra Spinal Muscular Stimulation



Mushawar et al., IEEE TNSRE, 2002

Intraspinal Microstimulation (ISMS)

- Advantages
  - ☺ Requires very low stimulation currents
  - ☺ Generates smoother muscle contractions, better recruitment, and some synergies
- Disadvantages
  - ☹ Not yet proven effective for overground walking
- Would benefit from compact, implantable controller



Source: Saigal et al., 2004

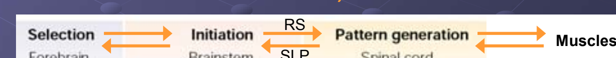
State of the Art: Commercial Locomotion Prostheses

- Parastep system uses FES of PMA (FDA approved in 1994)
- Designed as external (non-implanted) system
  - Surface FES electrodes
  - Hand-switches on walker control step timing
- Some work on automatic controllers, some neural nets [Strange & Hoffer, 1999; Fisekovic & Popovic, 2001; Abbas 2001; Guevremont et al., 2007]
- Little motivation for compact, implantable controller

Source: Sigmedics, Inc.

Our Approach

- Previous approaches ignore CPG and focus on controlling muscles to generate locomotion
- We propose to directly control the CPG and use it to generate locomotion
- Basic idea is to recreate natural neural control loop in an external artificial device (i.e. replace tonic and phasic descending inputs to the CPG with electrical stimulation)



Source: Grillner, Nat Rev Neurosci, 2003

Responsibilities of Locomotion Controller

1. Select Gait
+ specify desired motor output
  - phase relationships
  - joint angles

4. Control Output of CPG
+ phasic stimulation (efferent copy required for precisely-timed stimuli)
  - convert baseline CPG activity into functional motor output
  - correct deviations
  - adjust individual components
  - adapt output to environment

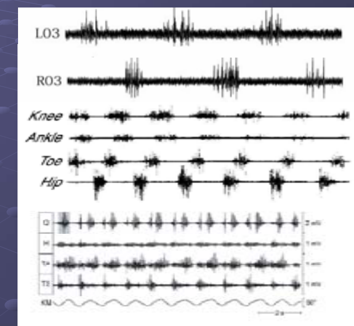
3. Generate "Efferent Copy"
+ monitor sensorimotor state
  - external sensors on limbs
  - internal afferent recordings

2. Activate CPG
+ tonic stimulation initiates locomotion
  - epidural spinal cord stimulation (ESCS)
  - intraspinal microstimulation (ISMS)

Select gait ~ brain
Activate CPG ~ brainstem (MLR)
Efferent copy ~ efferent copy
Enforce/adapt output ~ phasic RS

Is It Possible?

- 25+ years of evidence that the CPG can be reactivated after SCI [Cohen & Wallén, 1980]
  - ESCS can initiate CPG activity in humans with complete SCI [Dimitrijevic et al., 1998]
  - ISMS can initiate CPG activity in cats with complete SCI [Guevremont et al., 2006]
- Problem: activation signal provides only coarse control over CPG
  - Can turn CPG on and off
  - Baseline activity is inconsistent
  - Not adaptive to environment
- Functional locomotion requires adaptive, cycle-by-cycle control (normally provided by the brain)
  - 1+ year of evidence that CPG can be controlled on a cycle-by-cycle basis by an external device [Vogelstein et al., IEEE TNSRE, 2006]
- Ignore balance issues for now; intend to use walker for stability



Source: Mellen et al., J Neurophys, 1995; Grillner & Zangger, Acta Phys Scand, 1984; Minassian et al., Spinal Cord, 2004

Is It A Good Idea?

"The [spinal] cord contains a number of more or less complicated mechanisms capable of producing, as reflex results, coordinated movement altogether similar to those which are called forth by the will. Now it must be an economy to the body, that the will should make use of these mechanisms already present, by acting directly on their centres, rather than it should have recourse to a special apparatus of its own of a similar kind."

– M. Foster, Textbook of Physiology (1879)

- Summary: why should the brain "reinvent the wheel" when the spinal cord already does so much?
- Relevance: our approach is to maximally utilize CPG and spinal cord functionality remaining after SCI to take advantage of existing spinal "intelligence" instead of recreating everything in an external device
  - Muscle synergies
  - Recruitment order
  - Coordinated actions

Components of the Proposed Locomotion Controller

- Activation system
  - Implanted epidural (ESCS) or intraspinal (ISMS) electrodes
  - Tonic stimulation to activate CPG
  - "Outsourced" to other labs (i.e. already being addressed by independent researchers)

Components of the Proposed Locomotion Controller

- Activation system
  - Implanted epidural (ESCS) or intraspinal (ISMS) electrodes
  - Tonic stimulation to activate CPG
  - "Outsourced" to other labs (i.e. already being addressed by independent researchers)
- Control system
  - Specifies desired motor pattern (gait)
  - Generates efferent copy from current sensorimotor state
  - Enforces desired output:
    - ☺ Control activated CPG with precisely-timed (phasic) spinal cord stimulation {à la RS system}
    - ☹ Directly control the muscles with inactive CPG {à la FES}

Gait Controller (GC): Proof-of-concept in hardware

Phase Controller (PhC): Proof-of-concept in software

State of the Science

- Existing technologies for proposed neuroprosthesis
  - Epidural spinal cord stimulation (Dimitrijevic et al., 1998; Minassian et al., 2004)
  - Intraspinal microstimulation (Guevremont et al., 2006; Saigal et al., 2004)
- Alternative rehabilitation strategies
  - Spinal cord regeneration (Bradbury & McMahon, 2006)
  - Partial body-weight support training (Carhart et al., 2004; Dietz & Harkema, 2004; Reinkensmeyer et al., 2006; Abbas et al., 2006)

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  - Phase controller: *in vitro* results
- Ongoing and future research
  - Adaptation and Learning: *in roboto*
- Conclusion

Model Systems

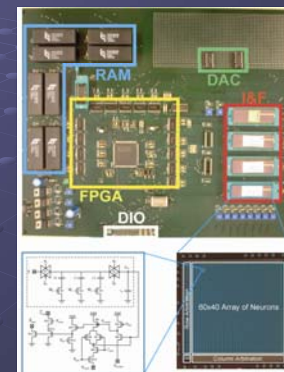
- Model system 1: Cat
  - Used to study locomotion for almost 100 years
  - Application: Gait controller
- Model system 2: Lamprey
  - Used to study CPG and spinal motor control for over 25 years
  - Application: Phase controller
- Model system 3: Legged Robots
  - Provides a reproducible platform to test out algorithms for real-time adaptation
  - Application: Gait shape, transition and controller

Hardware Development: Gait Controller

- Goal: develop a hardware system that can prescribe appropriate motor output based on pre-defined gait and current sensorimotor state
- Justification: need to know what the biological CPG is doing at all times and what we want it to do next in order to effectively control it
- Approach: build a silicon model of biological CPG, i.e. a neuromorphic silicon CPG chip (SiCPG)
- Why neuromorphic SiCPG?
  - Biological system provides good model for functions we want to implement
  - Neuroprosthesis should be implantable
    - Alternative solution: robotics approach—compute gait by inverse dynamics (computation- and power-intensive)
    - Neuromorphic circuits can be compact and low-power
  - Compatible with both muscle (FES/ISMS) and spinal (phasic CPG) control schemes

Reconfigurable Integrate-and-Fire Array Transceiver (IFAT)

- Designed as a general-purpose cortical array
  - Four custom mixed-signal VLSI chips with 2,400 neurons each
  - Up to 4,194,304 “virtual synapses” in RAM, each with programmable weight
  - Microprocessor routes spikes between cells via AER
- Ideal for prototyping large-scale neural networks with real-time operation
  - Combinatorial Attractor model of hippocampal place cells
  - Reisenhuber & Poggio model for object recognition network

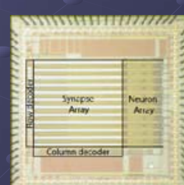


Source: Vogelstein et al., IEEE TNN, 2006; Vogelstein et al., Neural Comput, 2007

Silicon CPG Chip (SiCPG)

- Designed specifically for CPG networks
  - Intended to be standalone system after programming
  - 24 fully-interconnected (hardwired) silicon neurons
  - Continuous-time external inputs for sensory feedback
  - Early version of programmable synapses based uses an array of multiplying DACs
  - New models uses programmable synapses based on floating gate transistors (FGT)
    - Based on 9-T OTA
    - Multiplies input by weight stored on FG diff pair (programmable gated conductance)
    - Facilitates evaluation of different CPG network topologies
  - Programmable cell properties: refractory period, SFA, pulse-width
  - Uses direct synapses on the neurons and neurons act directly on motor system

CPGv2 (Tenore et al., 2004)



CPGv3 (Tenore et al., 2006)

Source: Tenore et al., Proc IEEE ISCAS, 2005; Tenore et al., Proc IEEE ISCAS, 2006

In Vivo Testing of SiCPG Gait Controller

- Goal: apply hardware to locomotion controller
  - Demonstrate that SiCPG can function as a Gait Controller *in vivo* (i.e. prescribe appropriate motor output in real-time based on pre-defined gait and current sensorimotor state: I.e. generate our “Efferent Copy”)
- Procedure:
  - Design CPG network to produce forward walking; specify gait in terms of:
    - Phase relationships between muscles
    - Joint angles for swing, stance, etc.
  - Program CPG network onto SiCPG chip
  - Use external sensors on limbs to provide sensory feedback to SiCPG chip
  - Use output of SiCPG chip to control locomotion
  - → *For testing purposes, use intramuscular (IM) electrodes to stimulate muscles directly (not phasic CPG control)*
    - Causes rapid fatigue and has other problems, BUT...
    - Directly controlling all motor activity in closed-loop (by controlling the muscles) verifies that we can use the current state to prescribe appropriate motor output
      - Output of limbs ~ CPG activity (efferent copy)
    - Simplifies testing GC component (biological CPG inactive)
    - Can be extended to phasic control of activated CPG (next section)

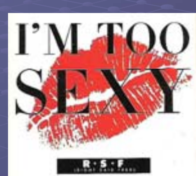
In Vivo Testing of SiCPG Gait Controller

- Animal model: cat
  - Well-characterized locomotor system; studied for over 100 years
  - Our collaborators have protocol to use deeply anesthetized cat as model of paralysis—convenient experimental preparation
  - Details
    - Experiments were conducted at University of Alberta with Vivian Mushahwar
    - Three adult male cats were anesthetized and implanted for acute experiments
    - Hip angle and ground reaction force sensors provided sensory feedback to SiCPG chip
    - SiCPG chip's output controlled 12 IM electrodes implanted cat's hind limbs to generate locomotion

Cat Walking 101

- First task: design a CPG network to specify motor pattern for cat locomotion
- To design a CPG network, it is useful to first know the normal locomotor patterns observed during cat walking

Cat Walking 101



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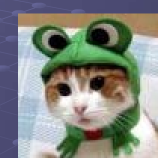
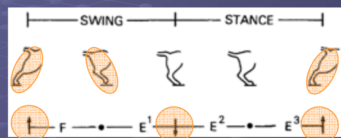
Cat 101: Basics

- Cats are cute, furry, quadrupedal mammals
- Typically, they are found chasing mice, Tweety birds, Odies, and fish
- For reasons not entirely clear, their hair falls out after cryogenic freezing



Cat Walking 101

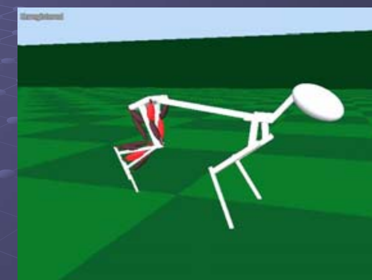


Source: Goslow et al., J Morphol, 1973;
M. Philippson, Trav Physiol Solvay, 1905

- First task: design a CPG network to specify motor pattern for cat locomotion
- To design a CPG network, it is useful to know the normal locomotor patterns during cat walking
  - Forward walking has a relatively simple motor pattern
    - Extensors and flexors are active in counterphase (i.e. at opposite times)
    - Hindlimbs alternate between stance (extension) and swing (flexion) phases (~70-30 duty cycle)
    - Transitions from stance to swing and vice-versa are triggered by two main proprioceptive inputs
      - Hip angle [Grillner and Rossignol, 1978]
      - Ankle load [Duysens and Pearson, 1980]
  - Gait suitable for implementation in CPG network in hardware
    - Question: how to convert this into language of CPG?
    - Answer: look at existing "rules" postulated to control biological hindlimb stepping

Cat Walking 101

- IF-THEN formulation of "rules" governing hind limb stepping in cats:
  - Stance-to-swing transitions:
    - *IF* ipsilateral hip is extended
    - *AND* ipsilateral limb is unloaded
    - *AND* contralateral limb is bearing weight
    - *THEN* initiate flexion in the ipsilateral limb
  - Swing-to-stance transitions:
    - *IF* ipsilateral hip is flexed
    - *THEN* initiate extension in the ipsilateral limb

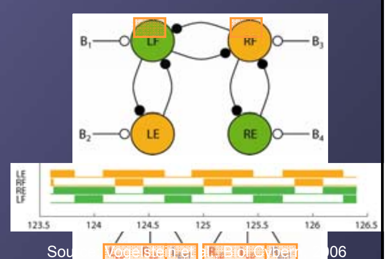


Source: Ekeberg and Pearson, J Neurophys, 2005

Source: Saigal et al., IEEE TNSRE, 2004;
Prochazka, Can J Physiol Pharmacol, 1996;
Guevremont et al., J Neurophys, 2007

Designing the Gait Controller's CPG Network

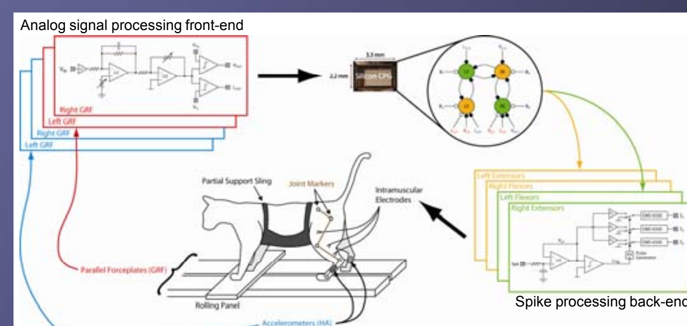
- Patterns in normal walking and IF-THEN formulation provides basis for CPG network
- Incremental design process, starting with the basics
  - Extensors and flexors are active in counterphase
  - Hindlimbs alternate between stance (extension) and swing (flexion) phases with roughly 70-30 duty cycle
  - Transitions from stance to swing and vice-versa are triggered by two main proprioceptive inputs
    - Hip angle: inputs indicate degree of left/right extension/flexion
    - Ankle load: inputs indicate degree of left/right loading
- Extensible: replace flexor and extensor neurons with hip/knee/ankle subpopulations
- Structure similar to biology-based models [Pearson, personal comm.]



Source: Vogelstein et al., IEEE TBME (submitted)

- Synaptic weights on bias, sensory, and lateral inhibitory inputs, along with rate of SFA, determine whether swing/stance (extensor/flexor) transitions are timed or sensory-driven
  - For these experiments, cats were allowed to walk at self-driven pace

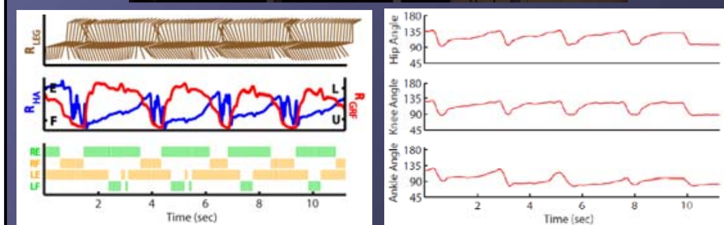
Gait Control System



Source: Vogelstein et al., IEEE TBioCAS, (submitted)

- 12 pairs of IM electrodes: 3 each for left/right hip, knee, and ankle extensors/flexors
- Two types of sensory data were collected for each leg
  - Hip angle (HA)
  - Ground reaction force (GRF)

Results: SiCPG Chip Controls Locomotion in a Paralyzed Cat



Source: Vogelstein et al., IEEE TBioCAS (submitted)

Summary of Results: *In Vivo* Testing of Gait Controller

- SiCPG is capable of implementing CPG networks for walking gaits and prescribing appropriate motor activity in real-time
  - First demonstration of a neuromorphic chip controlling functional behavior in an animal (i.e. it could replace its biological equivalent in a paralyzed cat)
  - Verified that SiCPG-based Gait Controller knows the current motor state (efferent copy) and what to do next; required for phasic control of an activated CPG
- Next set of experiments demonstrates how to use phasic spinal cord stimulation to control the CPG and motor output
  - Instead of having SiCPG chip control muscles directly, we want to:
    - Activate the biological CPG
    - Have the SiCPG chip run in the "background" and tell us when to intervene with phasic spinal cord stimulation
      - Caveat: next experiments use a different (simpler) model system, so we used a software equivalent of the SiCPG chip to execute these functions

Responsibilities of Neuroprosthesis

1. Select Gait
+ specify desired motor output
- phase relationships
- joint angles

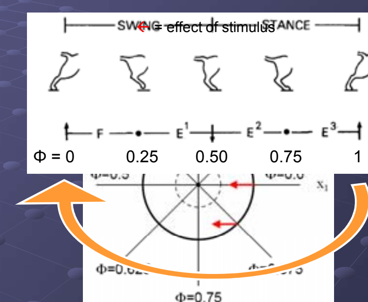
4. Control Output of CPG
+ phasic stimulation (efferent copy required for precisely-timed stimuli)
- convert baseline CPG activity into functional motor output
- correct deviations
- adjust individual components
- adapt output to environment

3. Generate "Efferent Copy"
+ monitor sensorimotor state
- external sensors on limbs
- internal afferent recordings

2. Activate CPG
+ tonic stimulation initiates locomotion
- epidural spinal cord stimulation (ESCS)
- intraspinal microstimulation (ISMS)

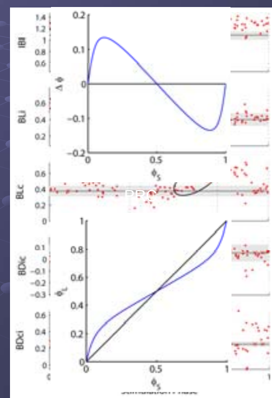
Nonlinear Oscillators 101

- CPG can be characterized as a high-dimensional nonlinear system in a limit cycle oscillation
  - Each step represents one revolution
  - Phase Φ in S^1: [0, 1]
  - CPG's state variables generally unknown (internal properties of neurons)
    - We don't care about variables, just limit cycle
    - Regardless of state space, effects of fixed perturbations to a nonlinear oscillator are likely to vary as a function of phase



Nonlinear Oscillators 101

- Standard techniques:
  - Phase-response curve (PRC)
  - Phase-transition curve (PTC) aka Poincaré map
- Our technique: phase-dependent response (PDR) plots
  - Advantage: simultaneously illustrates effects of stimulation on any observable output of the nonlinear system (no state variables necessary)
  - Descriptive: illustrates how stimulation affects all relevant output dimensions
  - Prescriptive: specifies when to stimulate to achieve specific output

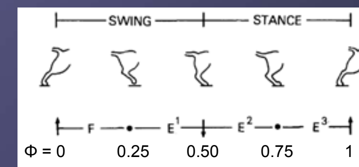


PTC

Source: Vogelstein et al. (in preparation)

Nonlinear Oscillators 101

- CPG can be characterized as a high-dimensional nonlinear system in a limit cycle oscillation
  - Each step represents one revolution
  - Phase Φ in S^1: [0, 1]
  - CPG's state variables generally unknown (internal properties of neurons)
    - We don't care about state variables, as long as there's a limit cycle in some space
    - Regardless of state space, effects of fixed perturbations to a nonlinear oscillator are likely to vary as a function of phase



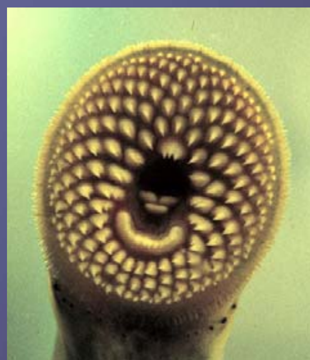
CPG as Nonlinear Oscillator

- Goal: show that phasic stimulation of the spinal cord can manipulate the output of the CPG
  - Use analytical techniques for nonlinear limit cycle oscillators and apply them to CPG
  - Standard techniques: phase-response curve (PRC) and phase-transition curve (PTC)
  - Our technique: phase-dependent response (PDR) plots
    - Advantage: simultaneously illustrates effects of stimulation on any observable output of the nonlinear system (no state variables necessary)
    - Descriptive: illustrates how stimulation affects all relevant output dimensions
    - Prescriptive: specifies when to stimulate to achieve specific output
- General experimental protocol
  - Activate CPG (i.e. initiate limit cycle oscillations)
  - Apply stimuli at all phases throughout locomotor cycle
  - Measure effects of stimulation on all parameters of locomotion as a function of phase (PDR)
    - Cycle period
    - Burst length (duration of muscle activity)
    - Burst delay (duration between activity in different muscles)

CPG as Nonlinear Oscillator

- Model system: Lamprey (primitive fish) — NOTE: Not a cat
  - Why not a cat?
    - These experiments were the first attempt (ever?) to use phasic spinal stimulation to control CPG, so we wanted to start with a simple prep
    - Spinalized cats are expensive and hard to care for
  - Benefits of lampreys:
    - Cheap, plentiful, and convenient experimental preparation
    - Standard model for studying locomotion for over 30 years
    - Very well-characterized CPG and spinal cord
    - Simple motor output (good for initial testing)
  - Working assumption: lamprey results can be translated to cats, humans
    - Basic elements of CPGs are conserved throughout vertebrate phylogeny
    - General principles of CPG-based control should apply to all vertebrates
    - We've selected the most convenient model system for these experiments
    - Will translate species-specific details to cats and humans (electrode type, placement, gait, etc.) after proof-of-concept

Lamprey 101

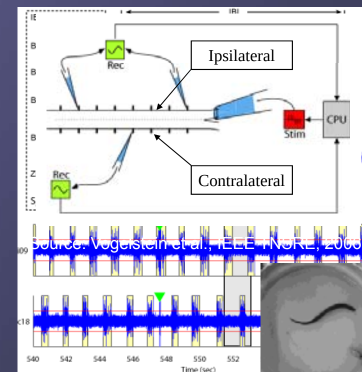


Business end of a lamprey

Lamprey-related casualty

CPG as Nonlinear Oscillator

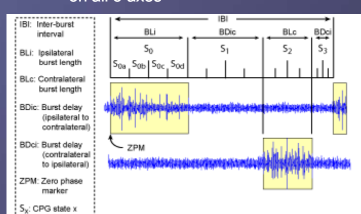
- Specific experimental protocol
  - Excise spinal cord
  - Initiate CPG activity with bath application of D-glutamate: "fictive swimming"
  - Record motor outputs on ventral roots
  - Apply suction electrode for stimulation at rostral end
  - Stimulate at 100 phases throughout CPG cycle
  - Measure effects of stimulation on all parameters of fictive locomotion as functions of phase (PDR)
    - Cycle period (IBI)
    - Burst length (BLi, BLc)
    - Burst delay (BDic, BDci)

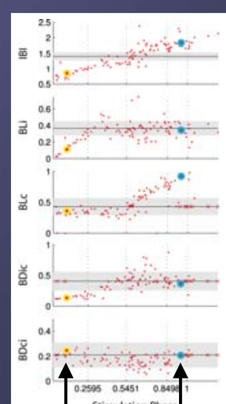


Source: Vogelstein et al., IEEE TNSRE, 2006

PDR Characteristics of Lamprey Spinal Cord

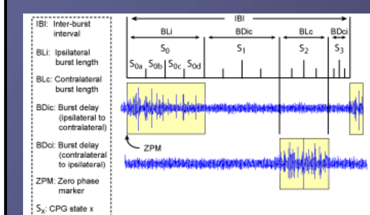
- Results from one experimental trial (PDR plot)
  - X-axis: Stimulation phase (%)
  - Y-axis: Measured burst parameter
  - Same stimulus applied at 100 different phases
  - Effects of each stimulus are plotted on all 5 axes

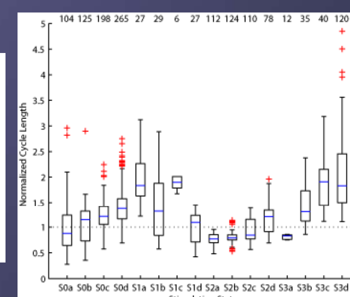




a PDR b

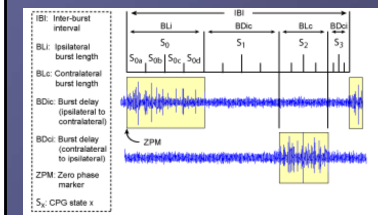
Results: Cycle Length Modulation

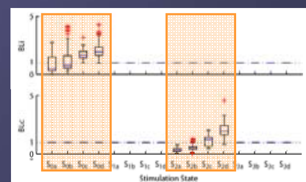




Source: Vogelstein et al., IEEE TNSRE, 2006

Results: Burst Length/Delay Modulation





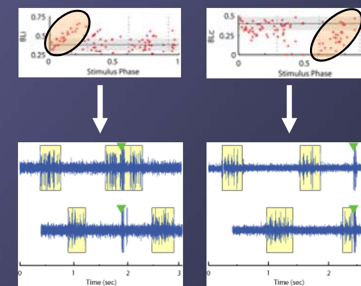
Independent control; limited in time

Source: Vogelstein et al., IEEE TNSRE, 2006

Summary: Phase-Dependent Responses

- Results so far:
  - Spinal cord stimulation can alter CPG output
  - Effects of stimulation are functions of phase
  - PDR specifies when to stimulate to affect a specific parameter of locomotion

Examples:
  - Increase burst length
  - Decrease burst length



Long Burst (ipsilateral) | Short Burst (contralateral)

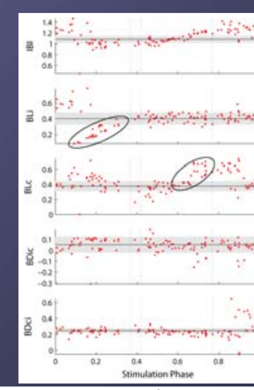
Application: Control CPG via Phasic Spinal Stimulation

- Instead of merely observing effects of stimulation, *choose* a specific desired motor output and stimulate to achieve it
- Procedure
  - Determine desired motor pattern (e.g. BLi = 0.3 sec, BLc = 0.25 sec)
  - Measure PDR curves for specific stimulus
  - Use PDR curves to determine appropriate stimulation phase(s) to effect desired output
  - Monitor CPG activity and measure phase in real-time
  - Apply stimulation each cycle at appropriate phase(s)

Experiment: Control CPG in Real-Time via Phasic Spinal Stimulation

- Goal: Control ipsilateral and contralateral burst length by phasic stimulation of lamprey spinal cord
- Observed PDR shows mostly independent control of BLi and BLc (some overlap)
- Can choose value for BLi or BLc by doing linear regression and solving for stimulation phase

Example:
  For BLi = 0.3 sec, $\Phi = 0.21$

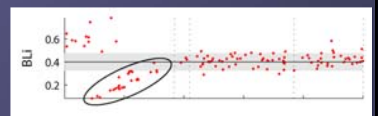


$\mathrm{BLi} = 1.24\phi - 0.03$ (seconds), $R^2 = 0.79$, $\phi \in [0.1, 0.35]$
$\mathrm{BLc} = 1.04\phi - 0.18$ (seconds), $R^2 = 0.60$, $\phi \in [0.45, 0.75]$

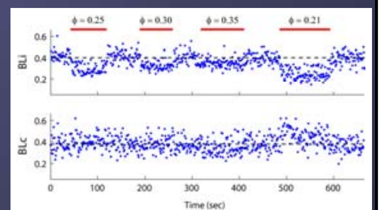
Source: Vogelstein et al. (in preparation)

Results: Control of Ipsilateral Burst Length

Φ	Predicted BLi	Actual BLi
0.25	0.28	0.29
0.30	0.34	0.33
0.35	0.40	0.35
0.21	0.23	0.25



$BLi = 1.24\phi - 0.03$ (seconds), $R^2 = 0.79$, $\phi \in [0.1, 0.35]$

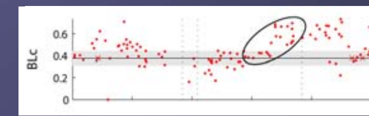


- Applied stimuli each cycle at specified phase for approximately 100 cycles
- Desired results
  - ✓ Predictable effects
  - ✓ Stable responses
  - ✓ No permanent shifts
  - × Interaction between BLi and BLc at some phase/amplitude combinations

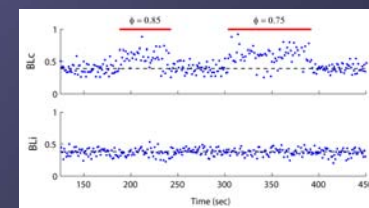
Source: Vogelstein et al. (in preparation)

Results: Control of Contralateral Burst Length

Φ	Predicted BLc	Actual BLc
0.85	0.70	0.61
0.70	0.55	0.56



$BLc = 1.04\phi - 0.18$ (seconds), $R^2 = 0.60$, $\phi \in [0.45, 0.75]$

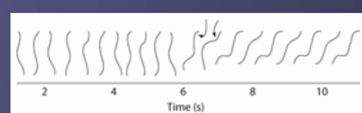


- Applied stimuli each cycle at specified phase for approximately 100 cycles
- Desired results
  - ✓ Predictable effects
  - ✓ Stable responses
  - ✓ No permanent shifts
  - ✓ Independent control of BLi and BLc

Source: Vogelstein et al. (in preparation)

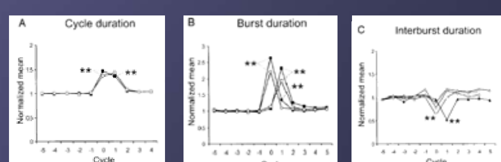
Steering Swimming

- Ideal: use phasic spinal stimulation to control CPG and motor output and steer lamprey swimming ("remote-control lamprey")
- Practical goal: reconstruct data showing that phasic stimulation can replicate specific gait (e.g., turning) by controlling output of the CPG
- We want to show that precisely-timed external stimulation can functionally replace brain-controlled phasic RS input



Source: Vogelstein et al., 2006

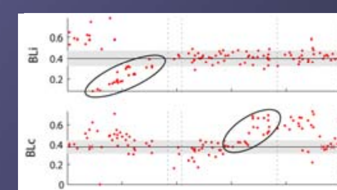
CPG/motor output during normal, brain-controlled turning (via phasic RS input)

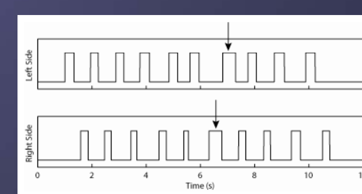


Source: Fagerstedt & Ullen, 2001

Steering Swimming

- Procedure
  - Measure control parameters and PDR for individual lamprey
  - Choose stimulation phases to modulate burst lengths on left/right sides (assume two electrodes and symmetric response) to create turning gait
  - "Simulate" bursting and effects of stimulation by drawing parameters from experimental distributions
    - Draw 10 cycles of CPG output
    - Draw effects of stimulation during cycles 6 & 7 at appropriate phases (intended to create turning gait)
    - Collect results from 100 simulated "turns"

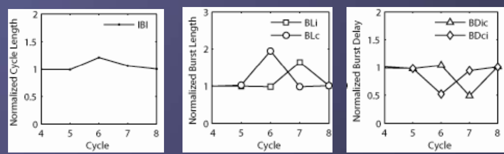




Source: Vogelstein et al., 2006

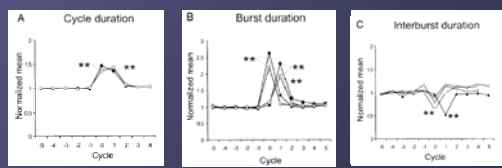
Results: Steering Swimming

Neuroprosthetic control via external stimulation (average effects)



Source: Vogelstein et al., 2006

CPG/motor output during normal, brain-controlled turning (via phasic RS input)



Source: Fagerstedt & Ullen, 2001

- Conclusion: locomotion controller can functionally replicate output of natural neural control system through phasic spinal cord stimulation

Summary of Results: Phasic Control of Locomotion

- Spinal cord stimulation affects motor output
  - Effects of stimulation are functions of phase
  - Effects tend to be isolated in time
- CPG can be controlled by phasic stimuli
  - Independent control over individual parameters of locomotion
  - Reliable and predictable output based on PDR
  - Consistent effects over multiple cycles of stimulation (no short-term adaptation)
- Reconstructed data show that external phasic control of CPG is functionally similar to natural brain control; can effect specific motor pattern (e.g., turning gait)
  - Proof-of-concept for Phase Controller
- Relevance to other experimental preparations:
  - Expect phasic spinal cord stimulation to modulate CPG output in cats, humans, etc.
  - Electrode design, placement, quantity, and stimulus will vary
  - Experimental design will be similar: apply stimuli, measure response of CPG as function of phase and use PDR curves to prescribe stimulation phase

Presentation Outline

- Introduction
  - Central pattern generators
  - Spinal cord injury
  - Proposed neuroprosthetic system
- Experiments & results
  - Model systems
  - Phase controller: *in vitro* results
  - Gait controller: *in vivo* results
- Ongoing and future research
  - Adaptation and Learning: *in roboto*
- Conclusion

On-Going Work

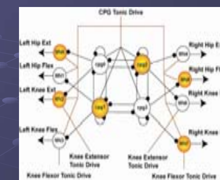
- Investigate effects of continuous control of CPG via phasic stimulation (in lamprey)
  - Cumulative effects when stimulation is applied for many consecutive cycles
  - Interaction terms when multiple stimuli applied within a cycle
- Investigate phase-dependent effects of spinal cord stimulation in cats
  - Find effective stimulation loci (same as location of ISMS synergies?)
  - Determine number of electrodes needed for independent control of motor parameters
  - Generate PDR curves to validate method
- Create convenient test platforms for technology development
  - Animal studies limit number of trials per day/week due to muscle fatigue, dosing limits, cost, etc.
  - Difficult to test real-time control loops in simulation (need a good model); don't want to waste animals perfecting technology
    - Biomorphic robots & neuromorphic chips as test platform?

Example Application for Bio/Neuromorphic Testbed

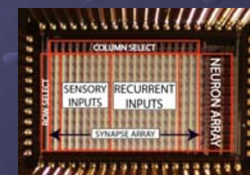
- Developing hardware/software for on-line (real-time) phase control
  - Condition signals
  - Detect bursts
  - Measure phase
  - Apply stimulation
- Motivation for using testbed: initial experiments had technical difficulties
  - Burst detection algorithm
  - Stimulation timing issues
  - Real-time operation
- Requires interactive model of CPG
  - Phase-dependent response to stimulation
  - Intrinsic noise sources and variability
- Bonus features
  - Interaction between multiple stimuli per cycle would allow for developing analytical tools and coping strategies
  - Motor output would allow for studying neuro-motor delays
  - Could operate “faster than real-time”

Bipedal Robot + CPG Chip

- Goal: Use artificial motor system to develop on-line phase control infrastructure (for future use in animal studies)
- Materials:
  - Partially-supported bipedal robot (“RedBot”)
    - Servo motors actuate hips, knees, and ankles
  - Reconfigurable silicon CPG chip
    - CPG controls hip movements, knee/ankles are passive
- Strategy: Use same experimental design as lamprey preparation to test new hardware
  - Choose desired gait
  - Measure PDR of CPG chip
  - Apply stimuli at specific phases

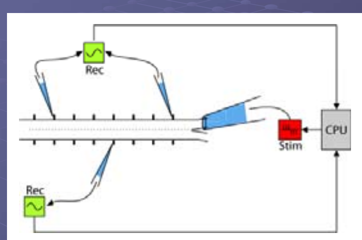


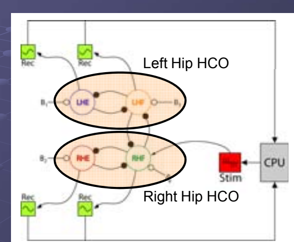
Source: Lewis et al., 2005



Source: Tenore et al., 2004

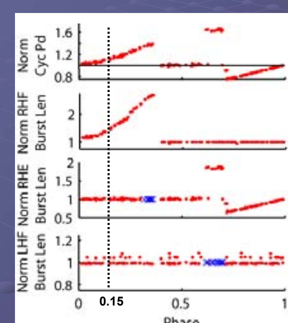
Experiment Design



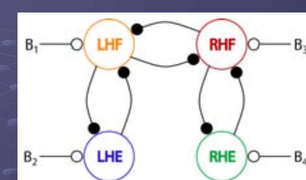


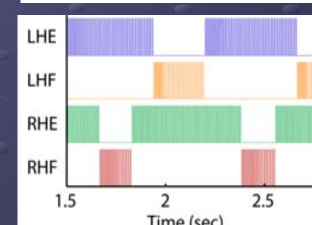
- Constraint: Use same hardware and software as used for lampreys
- Main purpose: Evaluate stimulation timing accuracy, check for correct identification of bursts, etc.
- Protocol:
  - Measure PDR by applying inhibitory stimulation to RHF at phases throughout CPG cycle
  - Observe effects on bursting of left/right extensor/flexor neurons
  - Apply stimulation each cycle to correct gait asymmetry (30/70)

PDR Characteristics



At phase 0.15, the combined effects are sufficient to equalize the burst durations of LHF/RHF and LHE/RHE

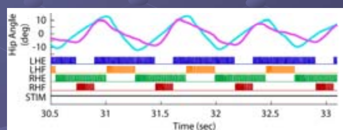




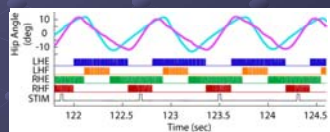
Source: Vogelstein et al., 2006

Results

- Bio/neuromorphic platform was effective tool for developing analysis/stimulation infrastructure
- Experimental hardware/software was tested successfully
  - CPG output monitored in real-time; stimulation applied each cycle
  - Prior to stimulation, the range of motion of the left hip was -11 to +11 compared to the right hip range of -8 to +8
  - During stimulation, the range of motion of both hips was approximately -12 to +12
- Initial experiments on lamprey confirm utility of testbed



Before



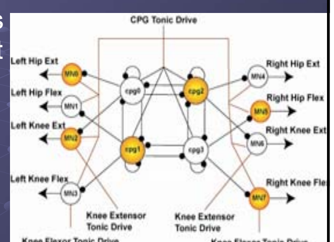
After

Source: Vogelstein et al., 2006

On-line Adaptation and Evolution of Walking Gaits

Improvements Required to the Locomotion Controller

- Need for more complex waveforms that allow actuation of independent muscles
  - Produce smoother stepping
  - Implement more bio-realistic muscle actuation profiles
- Need to dynamically change gait characteristics
  - Respond to changes in the environment and desire
- Automatic reconfiguration of CPG network
  - Increase in parameters with network complexity



Lewis et.al., ICRA 2005

IFA Neuron Model

- Simple model of spiking neuron with spike frequency adaptation

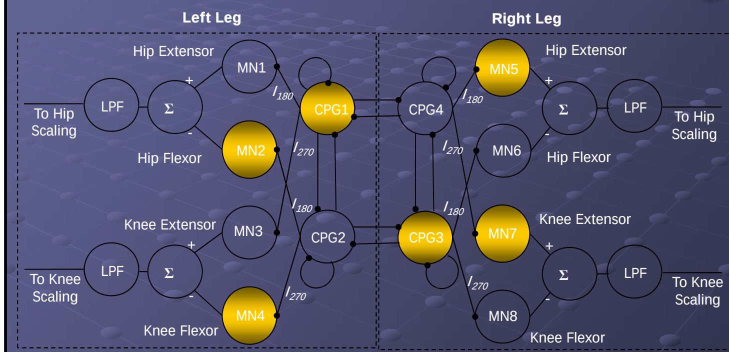
$$v_i' = \sum_{j=1, j\neq i}^{n} I_{j\to i} + a - bv_i + g_i(d - v_i)$$

$$if\ v_i > v_{thresh}\ then\ v_i = c$$

$$g_i' = \frac{e\delta(t) - g_i}{\tau}$$

Izhikevich, IEEE TNN, 2004

Canonical Walking Network



Apply Genetic Algorithm (GA) evolution to set network parameters

AMBA Genetic Algorithms

Walking Speed Fitness Function

$$T = \frac{1}{desired\ frequency}$$

$$error1 = \left(\frac{T}{2} - delay(CPG1, CPG2)\right)^2$$

$$error2 = \left(\frac{T}{2} - pulse\_width(CPG1)\right)^2$$

$$if\ CPG1_{end} = 0 \rightarrow error3 = 10000\ else\ error3 = 0$$

$$fitness(frequency) = (error1 + error2 + error3)$$

Human Walking Fitness Function

$$fitness = \frac{\sum_{\forall n}(desired\_angle - CPG\_angle)^2}{n}$$

Gait Fitness Function

$$f = \frac{1}{pulse\_width(CPG1) + pulse\_width(CPG2)}$$

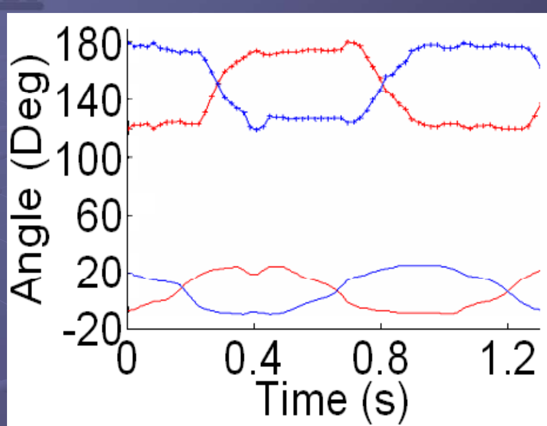
$$actualphase = delay(CPG3, CPG1) \times f \times 360$$

$$error1 = (desired\_phase - actualphase)^2$$

$$if\ on\_set(CPG3) < on\_set(CPG1) \rightarrow error2 = 100000\ else\ error2 = 0$$

$$fitness(gait) = (error1 + error2)$$

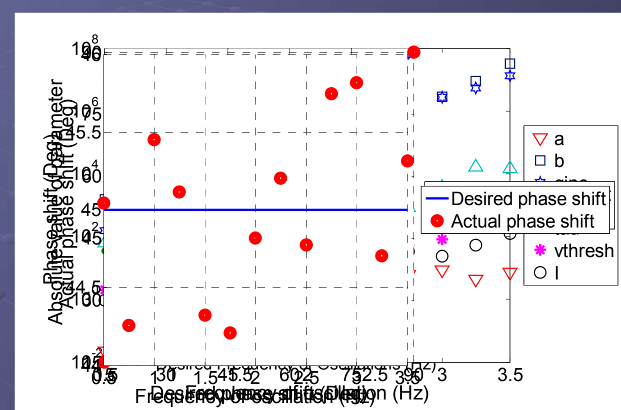
Simple Actuation Pattern



Hip Angles

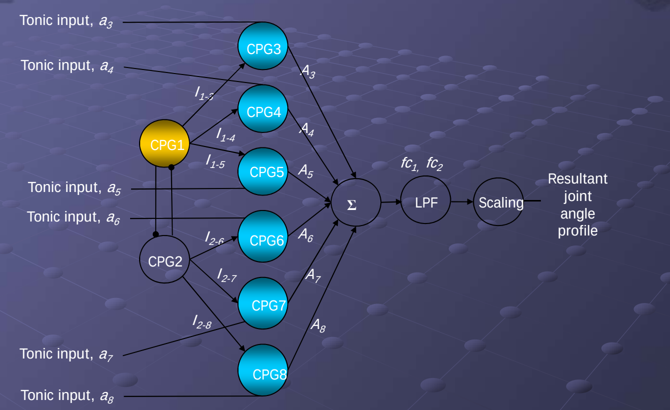
Knee Angles

Simple Actuation Pattern



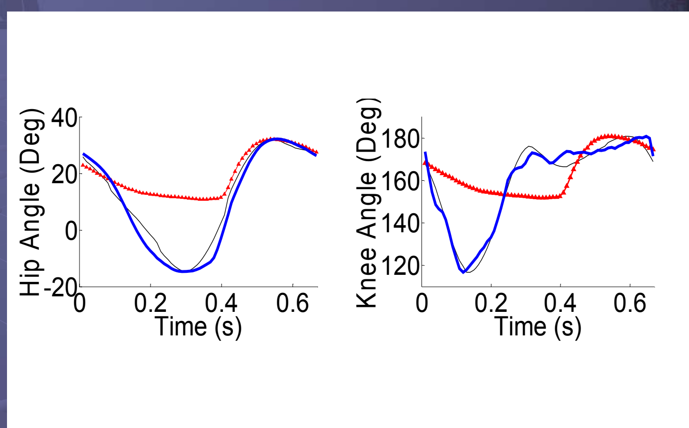
Implementation on RedBot

Creating Complex Actuation Waveforms



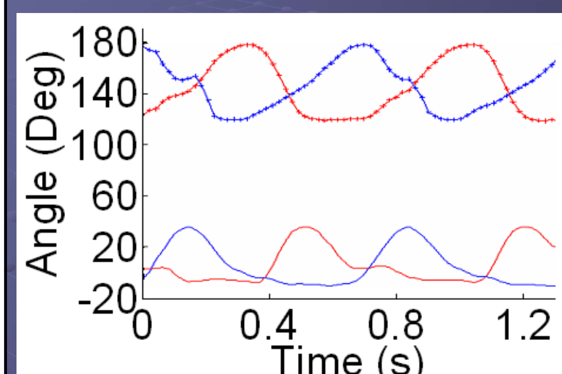
Human Walking Waveform from Vaughan et.al., 1992

Creating Complex Actuation Waveforms



Human Walking Waveform from Vaughan *et. al.*, 1992

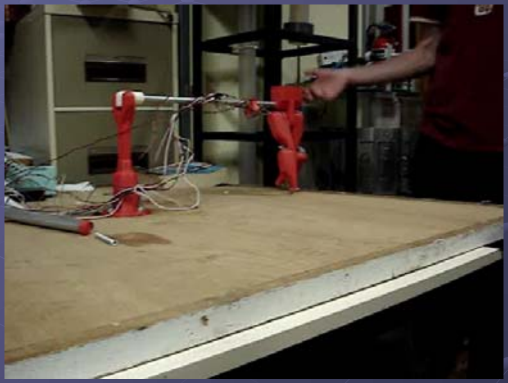
More Bio-Realistic Actuation Waveforms



Hip Angles

Knee Angles

Implementation on RedBot



Summary of Results

- Implemented elaborated CPG networks for more bio-realistic locomotion control
  - Based on our canonical locomotion network
- Used Genetic Algorithms to configure the network
  - Adaptive Mutation Breeder Algorithm
- Networks converged with three generations
  - Allowed near real-time implementation of GA on a PIC
  - Execution of IFA neurons on PIC was rate limiting step

Presentation Outline

- Introduction
  - Central pattern generators
  - Spinal cord injury
  - Proposed neuroprosthetic system
- Experiments & results
  - Model systems
  - Phase controller: *in vitro* results
  - Gait controller: *in vivo* results
- Ongoing and future research
  - Adaptation and Learning
- Conclusion

Conclusion

- We've proposed to use dynamic, cycle-by-cycle control of the CPG to restore locomotion after spinal cord injury
- Two components of a proposed locomotion controller were tested successfully
  - Neuromorphic CPG can generate desired motor output based on sensory input in real- time – *The Efferent Copy*
  - Stimulation of spinal locomotion circuits has repeatable phase-dependent effects on CPG output – *Brain Control*
- We have demonstrated adaptation and learning with CPG networks to control a legged robot
- Future work focuses on testing cumulative effects of stimulation, translating lamprey results to cat preparation, and adaptive/learning hardware development

Questions?