Biological approaches to Robotics:

Bio-inspiration

- Applications

Biomechatronic design

Biological system

Engineering: robots to invent

Science: robots to discover

Surgical robotics

Neuro robotics

Rehabilitation

Biorobotic science

Human model

World model

(Or animal, \text{interaction} robot model)

Phenomenon

Implementation in robot

Experiment

Biorobotic science

Autonomous robots, 21.

Effects of setae on locomotion (build artificial setae).

Models

Biomechanical model - Equ. of motion during muscle contraction

Robotic models may not perform like biological systems.
EARTH WORM LESSONS - "painless" colonoscopy (based on actuator mechanism in earthworm)

LEGGED ROBOTS - applications on compliant tissues.

SNAKE-LIKE ROBOTICS -

POLYCHAETE MARINE ANNEAL

Computational Models -
body shape control
(SimuWIN) → size/mass
data for anatomical links;
Force, Kinetics data

Undulatory Field Gait on Sand -
Turning Gait
In-place Rotational Gait

Jumping Robots - jumping (scale effects) -

V^2
Fr = \frac{\text{Physics of Jumping}}{g1}

Flying MicroRobots

Bronze # → minimized in small animals,
Hopping more efficient than walking
Long hind legs — longer dist./acceleration
enlarged femora — greater muscle mass

Frog-Hoppers,
Leaf-Hoppers.

Numerical Analysis

\[ \text{POSITION} \rightarrow \text{SPEED} \]

\[ \text{pixel} \rightarrow \text{MS} \rightarrow \text{vol} \rightarrow \text{MS} \]

\[ \text{contact force} \rightarrow \text{spring force} \]

\[ \text{JUMP} = 6 \times \text{height}, 3 \text{ body lengths/sec.} \]

Take-off action — leg morphology, variable gear ratio

\[ \text{GEAR RATIO} \rightarrow \text{FOOT POS} \]

Force pattern scaled to leg morphology
Preflexes — require less muscle power, passive dynamic walking.

Measure bending w/ optical sensors

Notochord — stiffen the body
Full, Cutoffsky, 2002 — Preflexes arise from stabilizing aspects of notochord

Prog Brain ANS 165, 221 (2007)
Average across segments.

STAN GREINER —

disks

Notochord
Effective locomotion — progressive wave.

Lamprey — vertebrate prototype.

Sensory Areas

\[ \text{Tectum} \rightarrow \text{BASAL GANGLIA} \rightarrow \text{CAG} \rightarrow \text{MOVEM} \]
OCTOPUS - infinite d.o.f → distributed control,
(muscular hydrostat).

RELAXATION
CONTRACTION
(combination of actions).

* transverse "1"
* oblique muscles
* longitudinal "1"

250% elongation

1.8% contraction in transverse muscle - most of contraction in arm.

* ELECTROACTIVE POLYMERS
* can create joints anywhere along hydrostatic arm.

IEEE ROBIO → STICKY BOT

PLANT ROBOTS → plants move at different time scales than humans.

TROPISMS - sensitive to water, light, gravity, very very primitive nervous system (sensory system).

PLANT ROOTS - use roots to penetrate soil, anchor themselves, mine soil for minerals (capillary strategy).

OSMOTIC ACTUATION - 3-cell model. 13hr steering.

2N of force, 13° (humidity sensor, accelerometer, microprocessor).
MULTI-PURPOSE USAGE OF ARTIFICIAL LEGS -

- Sensory data: proprioceptive sensors, higher density
- Reactive (reflexes, proprioception)
- Based on scorpion biology
- Behaviors (rhythmic, locomotion templates)
- Deliberative (planning, exteroception)

SCARABAEUS -

- Used for locomotion & grasping
- Piezo-electric load cell
- Peak in piezo = current (may/may not be an object there) → couple w/motor current
- Motor + Piezo = Grasp

ASGUARD - wheel design

Legend - effector (foot) design

- Claws into objects (stair, rock)

Habitat - Mars (40° slopes, changing rock composition, 7% 300°C gradient

Grabbing - fast detection (coordinates calculated only when object detected)

Bézier splines = CPGs under low-level control

Control -

- CPG control
- Trajectory control

Basic sawtooth pattern adaptive based on position.

Adaptive spring based on proprioceptive data
High current discrepancy \rightarrow \text{release spring control at low current discrepancy} \rightarrow \text{recoil spring} \rightarrow \text{end-effector}

Specific density of \text{AS GUARD V1 (fairly buoyant)}

\text{COMPLIANCE on some legs, but not others (mimics scorpion),}

\text{COMPLIANCE in body cavity (stiffness achieved via trial error). How would these things evolve?}

* \text{CLEARANCE is limited to extent of legs (beyond tip, grasping function is useless). Full-speed rotation of legs during swimming (robot loses control, capsizes).}

\underline{\text{INSECT FLIGHT}}

\text{ROBERT WOOD - create fly-size autonomous MAV (<200mg)}

\text{AERODYNAMICS - DICKINSON, SCIENCE, 1999}

\text{nearly horizontal symmetric wing trajectory consisting of a large stroke, rotation about longitudinal axis of wing.}

* Lift mechanisms dominated by unstable aerodynamic mechanisms.

* Rotational lift, symmetrical, periodic wingbeat freq. enhanced lift (unlike aircraft).

\text{BERKELEY MFL - 4 actuators, 30 joints (control phase w/ actuator inputs).}

\text{Keep inertial matrix as diagonal as possible.}

\text{THORACIC kinematics - compliant, parallel mechanisms \rightarrow transmission ratio (output - angular \rightarrow input - translational) \rightarrow minimize as much as possible.}

\text{THORACIC mechanics (actuators excite mechanically amplifying thorax to resonance),}

\text{DIRECT \& INDIRECT flight muscles (controls rotational capacity, not baseline trajectory).}
DYNAMICS – potential & kinetic energies. Derive wing volume for aerodynamics.

AIRFOILS – wings = anisotropic compliance, does this have a function? Recreate stiffness of veins & membrane, vein/membrane patterns – what are necessary & optimal combinations? Aspect ratio of width : span?
At low loads, trajectories are flat. Increased loads, increased flexure of joints.

ACTUATION – piezoelectric cantilevers

50° flapping, 40° rotation, 1000 Hz, thrust : weight = 2 : 1.

WINGSPACE – all variation in phenotype, play around w/parameters.

WALKING, CLIMBING, ETC.

300 dogs of 30 different breeds (do body mass, etc. have an effect on locomotion)?

SIEMENS NEUROSTAR (1000 x-rays per second), near HD-resolution.

Quadrupeds often mounted wrong (hip joint level to scapula, not shoulder joint).

BODY MASS no influence on biomechanics (scaled to single IGF-I allele regulates hindlimb length).

Leg length in dogs (SUTTER et al. SCIENCE).

INSPIRAT – moving in artificially designed spaces → looks for convergent evolution in morphology.
GRASPING EXTREMITIES - back is rigid, front is flexible (in lizard model).

Measure torque - in chameleon → place hand/foot exactly under center of gravity (along mediolateral axis) → almost no torque produced, limited rotation. *not true in humans or forelimbs in bipeds* (monosynaptic pathway to MNs for upper limbs only).

AIRARM - FESTO corporation → human working in human space (reachable volume for one arm).

SCIONIC → human reaching space using insect space. Pneumatic muscles inside robotic frame (like insect) to mimic human arm.

Smart Mechanics serves on control - lesion SMC using dyes & optical methods → more than ½ of sensorimotor cortex lesioned → no effect on reaching.

TARGET ANGLE - shoulder, elbow joint most variable for limb geometry. Target of control, most joints or muscles per se. Does triceps muscle local controller for limb knowing geometry?

CAICOVA, 1999 - triceps brachii = sensory adjustment muscle (connects shoulder plate & lower arm). TB is "ball" for local control of limb geometry. Spinal control can produce gait in decerebrate cats.
HEIKO HOFFMAN - motor learning, generalizing to new targets. KULLEN - chest muscles amplified to control roboprostheses (EMG upper body).

Very few control signals for many degrees of freedom → control dexterous arm with only a few signals.

ISSPEERT & SCHAAH → dynamic movement primitive is differential equation →

\[
\dot{v} = k(g - x) - DU + F(W, \Theta)(g - x_0)
\]

\[
\dot{x} = v
\]

Learning → change W
Generalize → change x

GISLER et al. → motor primitives in frog (spinal cord stores leg force fields).

# Small changes in goal may lead to extreme motions, whole movement scales relative to start-goal position.

POTENTIAL FIELDS - velocity vector - gradient relative to obstacle, start, goal.

Dynamic movement primitives are convergent force fields.

WALID FARHAD - Hugh Herr → capability of skeletal muscle to generate mechanical power → constraint IMPEDANCE MATCHING - role in mechanical energetics
Adaptive strategies to maximize muscle force.

WORKLOOP technique – (see JOSEPHSON) BILINEAR MODEL

periodic power output

of muscle

* no effects of antagonist muscles
* no load - muscle interaction
* add a passive spring mechanism to solve this

At appropriate freq., pair of muscle can do more work than they could alone

DYNAMICAL MODEL

\[ \int_0^T \text{power}(t) \, dt = \int_0^T F \cdot \text{net} \, dt \]

* more co-activation, more stiffness.
* Stiffness vs. resonance conditions.

\[ \gamma = \frac{\text{Pan}}{\text{Pa}+\text{Pn}} \]

\[ \gamma > 2 \text{ can be attained (synergy only)} \]

modulate joint stiffness?
favorable energetic conditions (at certain freq. of stimulation ranges).

Muscles as motors or dissipative elements?
12 dof quadruped (Boston Dynamics). Must handle ‘unseen terrain.’

PATH → FOOTSTEP → COG → INV. KINEMATICS

*minimum jerk planning

ALGORITHM:

- Terrain evaluation, scoring, determine current state & path.

Fixed, pre-computable cost path (not for locomotion).

KNEE CLEARANCE (front-behind) → different cost paths.

TEMPLATE TERRAIN SCORING → memory-based technique
- Current foothold positions → COG position determination
- COG trajectory → keep it straight (no lateral forces), minimize jerk.

Finite state automata for each foot (move forward or stay still). *General parameters are robust.

LEARNING & ADAPTATION — large variety of terrains, lots of open parameters. Supervised/Unsupervised learning.
- Static walk → 10.7 cm/sec, very rough terrain
- 8 cm steps at 7 cm/sec, climbs grades up to 30° (more w/better end-effector friction).
Muscles — Force

Aerodynamics — Force

Velocity

Neuromuscular output

Muscle physiology

Muscle

Hill muscle model

Aerodynamics

Compensation

Compensation

Flight behavior

Neuromuscular output

CNS

AG.

Tyson Hedrick

Perturbed Hovering — Manduca Sexta

Perurbation compensation in hovering flight — Perturbation compensation in hovering flight.
NEUROMUSCULAR OUTPUT – upregulation of flight motor, but not other aspects of muscle.

No feedback controller, more weight to be moved – greater muscle power output required.

Overall inc. in neural activation w/ inc. wingbeat freq. Potential ‘fast’ sensory modes.

NEURAL CONTROL FOR WALKING MACHINES –

6-legged & 2-legged robots

* biomechanics, neural control (CPG) (reflexes)

(higher control centers)

SWITCHING NETWORK – (VRNs → produces ‘shifts’ in movement).

NEURAL LEARNING CONTROL CIRCUIT – versatile reactive behavior

(startle, rep., wind-evoked escape behavior, phototropism)

* Nested loop design

reflexes for biped robots: Chaotic motion → self-untrapping

* no CPG, just based on spinal reflex mechanism

* learning control circuit at periphery

SENSORS → NEURAL PREPROCESSING → NEURAL CONTROL → OUTPUT

after 3 trials, robot can respond to assoc. learn (evades sound).

* Efference copy searching

* modify CPG module for generating gaits & chotic behav.

DISTURBANCE REJECTION – gains, efference copy through learning.
* BIOMECH, SPINAL MN, & REFLX levels of control.

does learning anti - catastrophic (does it stop falling over)? What are parameters?
If you continually change environmental parameters, learning will continue; change can’t be too catastrophic.

CUTKOSKY - Principles from locomotion.

DANTE → stiff links, powerful actuators (traditional robot design) → rate-for-failure high.

HEXAPEDAL - have a running hypothesis

test on robots

much more reliable than animals.

Cochroaches run over rocky terrain @ 50MPH. Don’t rely on vision, assume mechanical system will work.

adding compliance in leg doubles slip model.

Cochroaches - some legs specialize sprawled posture active thrusting force, passive hip (compliance) (reset equilibrium).

Mechanisms dampen, return forces selectively.

Hysteresis loop - low-inertia leg system, center of mass & low-amplitude sine wave, determines compliance at hip, along axis of leg.
Nature fundamentally anisotropic. Shape deposition manufacturing. Design object, produced in layers (parts embedded into robotic leg—no screws).

**ROUGH SURFACE CLIMBING**—Scansional surfaces

![Diagram of a cockroach]

- **SPRAWL** is highly specialized, underactuated mechanisms.
- Open-loop, clock-driven system.
- Clocks can be stable over a wide range of frequencies.
- Does not work in workspace setting.

Multiple solutions for multiple surface types, (soft to hard, even true of the gecko).

**COMPLIANT SPINES**—Cockroach climbing up a wall of glass beads. Foot very soft at compression (when first touch wall). Spines as they come into contact, stiffen & take on load.

Dressed stone — lower limit on roughness. Od in spine (vertebral column).

- **Smaller spines, more asperities on surface to latch on to. Also depends on weight.**

![Graph showing required force vs. robot weight against asperities/area]
SCALING SPINES TO LARGER ROBOTS — SMOOTH CLIMBING —
glass (better off using adhesion).

ADHESION — hierarchy of adhesive structures
(multiple mechanisms (setae, spatulae) for
various aspects of surface, (HIERARCHICAL COMPLIANCE).

FORCE BALANCING — , HALL EFFECT SENSOR + PASSIVE
limb compliance (F = [k] s x) pressure, force

toes curl w/1 df (differential)
uniform pressure across toe (ensures adhesion)
Electrical tape is not controllably sticky (sticks
w/o large amount of work done).

β-keratin, layered so that it is tacky (use
structured elastomer).

Dragging (adhesion), push directly down onto
surface (no adhesion). *Greatest amount of
FRICIONAL ADHESION

stickiness (compression
w/o shear forces)

\[ \text{Control foot}
\]
orientation +
internal

forces.

(linear programming

DIRECTIONAL ADHESION — pull harder on front
feet (FRICIONAL — shift to back feet)

smaller animals = more primitive adhesion
mechanisms.
MICROWEDGES - dynamic directional dynamic adhesion.  

FORCE PLATE - pull up force in non-directional adhesion (absent in directional).  

UNLOADED STATE - not much area contact.  

COMPLIANT HIERARCHICAL STRUCTURE - hard to model.  

WALK-TO-CLIMB transition, TAIL modeled as a frictionless point contact (used by Geck only when in trouble).  

MICHAEL DICKINSON - HIGHER-ORDER CONTROL OF LOCOMOTOR BEHAVIOR → Neuroethologist (natural behavior) sound localization in barn owls, etc. → Drosophila INTEGRATIVE APPROACH - AUTONOMOUS CONTROL:

SENS. FEEDBACK  

CNS  

motor commands  

MUSCULOSKELETAL SYSTEM  

KINEMATICS/ FORCES  

DYNAMICS/ ENVIRONMENT  

HIGHER-ORDER CONTROL  

TAKE-OFF → VISUAL NAVIGATION, OBSTACLE AVOID → PREDATOR AVOID  

ETHOME  

LOCAL EXPLORATORY SEX  

ODOR TRACKING  

flight initiation  

shocked (abrupt, recovers)  

in 10
Voluntary (Wingberg)

**Power to legs is 200% greater during escape (hormonally modified)**

Do flies jump away from a looming stimulus?

* Fly harder w/legs during escape takeoff.
* FLIES trade speed for stability (recover from large perturbations).
  * Neural control-mediated by vision, mechanosensory cues.
  * Flies jump in opposite direction of escape cue even when heading is in opposite direction (different movement strategies).
  * Azimuth of stimulus relative to 'dance' of fly.
* Compensate for postural state
  * COM motion vector, leg motion vector.
  * Fly compensates for COM initial state (CNS knows where COM is relative to legs).

* Fly biases jump away from escape stimulus.
* Flies jump away from stimulus even after wings are clipped.

Center of mass: pre-stimulus vs. pre-jump

<table>
<thead>
<tr>
<th>Jump Angle</th>
<th>Direction of jump vs. direction of center of mass</th>
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<tr>
<th>Lat. Movement prior to Jump</th>
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<th>COM</th>
<th>T2 tarsae</th>
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Stim, direction

Sensorimotor transformation
PREDATOR AVOIDANCE - exploratory behavior around larger objects; smaller objects, more avoidance.

OPEN-LOOP - fly's position cannot change size of stimulus.
SPOT Vs. STRIPE (closed-loop response).

VR system for flies (won't get in trouble landing on vertical edges).

- Like Tinbergen's innate object recognition,
- Ewert's stripes as worms (frog model).

BEHAVIORAL INTERACTIONS -
- chase, attraction, deflection, double stop, single stop

* can execute early phases of dance, but not later phases.
* triggered by different levels of stimulus energy, intensity.
ARCHIPELAGOS of cones: flies orient towards cones, explore them.
* in dark can't see them but when they bump into them still explore them.
* when they find a 'steep' cone, spend more time there.

* modulate locomotion by walking, not walking (Markov process).
* steep cones: larger stop durations

GEO-TAXIS
CONE

VISUAL ORIENTATION

use ferryboat captain's rule.
General principle of autonomous systems —

**AUDITORY DISCRIMINATION** — tells brain where object is in environment (azimuthal, quality of stimulus, appropriate response)

3 principles of autonomy: 
WHERE, WHAT, & WHICH MOTOR PROGRAM TO USE?

WHERE VS. WHAT
Pathways in human vision — context — appropriate motor responses.

P. Hunter Peckham —
Neuroprostheses for movement restoration. Leader in functional electrical stimulation.
Hand grasp devices —
Paralytic disorders & role of neural prostheses.

Paralytic disorders pervasive, take many forms (multi-system, congenital, acquired — at any age), injury heterogeneity.

Movement (manipulation, standing, locomotion).
Peripheral nervous system intact, CNS lesion.
Providing modest improvement makes huge difference.

**HAND PROSTHESIS** — turn on, off, inpatient as own control.
Triolo, Davis — swing through gait, can augment (swing-to) injury at level of C7.
Paraplegia → functional goal (standing), (walking) (hand grasp) → M10 - LEVEL TETRAPLEGIA (requires certain # of muscles). Surgical intervention — expand range of
motion in joint (if nothing there to move it, no good).

INTERVENTION:
* max. function of retained NS
* utilize damaged NS w/ interface
* have them work together
* don't damage regenerated tissue

STIMULATE muscle (small input, large output).

few muscles above injury, take signals out to control lots of damaged muscles below.

DEFINE what neural prosthetic must do.

User generates command signal (1-2 control signals), used simultaneously to control stimulator (regulates many stimulators). Command control 'hand open', 'hand closed' instead of individual digits, joints.

NERVE - depolarize nerve axons, action potential propagates (nonlinear output)

I/O - # of axons activated : stimulus delivered
* create/annihilate activity
* requires neural structures to be intact
Muscle-based: implanted on/in muscle near NMJ

Nerve-based: wrap around nerve, reconfigure nerve to access more fibers, clips that grasp onto nerve.

Nerve cuffs (upper/lower extremity)
Nerve block - sensory block, motor block.

Spastic jikos.

Block different action potential

Muscle

Command control - huge stimulus artifacts (block them), tend to swamp out myoelectric neural signal

* One device for one major function - recording from 2 different muscle sites.

MES (myoelectric stim.) -
* Bilateral hand control -
* Postural balance - C6 unilateral vs bilateral task (writing vs. opening a jar of peanut butter)

Enough torque produced to manipulate hair dryer, etc.

Synergistic activation - use deltoid to control triceps

Works

Does not work
COMBINED SYSTEMS - Bilateral (Hand & trunk, hand & bowel, etc).

TRIOLO, KILGORE, HOYEN → incomplete lesions are where this could help the most.

More natural control methodologies (neural signals), MULTI-CHANNEL STIMULATOR/TELEMETER (16-12 channels), reaching upper limits of tech.

Networked system (multiple stimulation channels).

Myoelectric control → excellent command signals, direct brain control underway.

FES & fatigue - voluntary control → rate & frequency modulation to control recruitment of motor units. High force activation, fatigue still a problem in extended lower-extremity model.

Muscle atrophy - due to disease, upper motor neuron lesion.

Muscle is plastic, increase/build muscle w/surface electrodes & put in cast, train again w/implanted electrodes.

Feedforward vs. feedback.

ANIMALS AS MODELS FOR ROBOT MOBILITY & AUTONOMY - NEUROMECH

MECHANICS CONTROL ENVIRO.

RUN, TURN, CLIMB.

BRAIN
CRUSE (1990) TINS, 13, 15-21 (insect gait mechanisms)

- How does stance switch to swing?
- COMPLIANCE (active/passive)
- STEPPING REFLEX
- INSECT GAITS
- ELEVATOR, SEARCHING REFLEX

# NELSON & QUINN, 1999

1) Mecharoach (mechanical mechanisms).
2) Explicit inverse kinematics.
3) NN implementation.


- Coupling & sharing sensory information.

MCKIBBEN artificial muscles
- 500 W/kg
- 10 N/gm
- 25% strain
- 2-10 Hz self-limiting force output

POWER: WEIGHT
- Motors scale up well, scale down badly.

(C 1x150W motor weighs less than 5x30W motors).

COCKROACH LEG
(CMG, KINEMATIC DATA) → "find" gait,

ACTIVE COMPLIANCE - adapts to conditions.

SIGNAL → SCASM

MUSCLE MODEL

JOINT CONTROL

control w/ very little processing power.

# EXP BRAIN RES, 1999, 126.
# J. EXP BIOI, 205 (JINDRICH &
Switchably compliant FULL).

Back brace for humans.

(CSWITCHING BETWEEN STIFF & COMPLIANT BRACES, SEE WHAT HAPPENS).

WHEEL-LEG-LEG CYCLE FUNCTION ("WHEQ")
Torsional Spring — leg hits something, gets stuck, spring winds up (passively move in phase), body joint for bearing & stability — frees up robot as it goes over rubble pile, complex surfaces, allows for wheg to claw up obstacle, reach out, grab obstacle, propel itself over it.

RHex (ICRA 2000) — 1) compliant legs, 2) compliance control system. Whegs do something w/out computational control (passive, mechanically robust).


Whegs w/legs of scotch tape — adhesion.

Stanislav Gorb — distributed inward grip
Gripper based on sea slug feeding —

Autonomy — brain guides 3-D motion for behaviors

Mark Willis — odor plume tracking behavior in flight.

Cricket phonotaxis circuit on whegs.

Tim Horiuchi — work on lat configuration.

Don't rely too much on global info, overlook local info.

Modulate rather than switching control.
PHYSICAL ADAPTATION - individual level.

Cortical areas in monkeys - locomotor control

MACAQUE $\rightarrow$ QUADRUPED $\rightarrow$ BIPED

$\text{MI, PMd} \rightarrow$ neural activity increases strongly w/ transitions

SYNTHETIC NEUROETHOLOGY -
behavior switching modeling according to neuromodulation (physiology).

PDW research -
passive mechanisms, simple mechanisms for control.

REACHING MOVEMENTS -

VELOCITY-dependent force field

adaptation of internal model

Generation of switching of internal model

Impedance adaptation

Fast & slow motor pathways in apsia.
EXPERIENCE-dependent behavior in crickets.

Mechanisms of social adaptation (animals alter behavior, respond to changing env. & interaction w/ each other).

ANTS, BEES (sociality, caste system)
CRICKETS, SILKWORM MOTH (solitary, phenomenal comm. only)
CRICKET FIGHTING (agonism)

NEUROPHYS, MECHANISM

SINGLE ANIMAL BEHAVIOR (AGONISM - based on release of cuticular substance)

GROUP SOCIETY BEHAVIOR

MALE-MALE:
Antennal fencing
(mandible fencing, establishes dominance)

MALE-FEMALE:
Calling song
(courts, courtship, copulation)

Cuticular substance - many specific hydrocarbons
Pheromone behavior (generally thought to be an on-off switch w/no plasticity).

Avoidance remains constant up to 60 min. after first exposure of pheromone

RX AVOIDANCE

900 600 300 0
1000 100 0

t (min)

OTHER ROBOTS FIGHTING

WANDERING STOPPING STAYING

FIXED PROB.

INTERNAL MODEL PARAMETER
\[ p = \alpha \text{ (} 0.01 < \alpha < 1 \text{)} \text{ prob. of losing at cricket fight} \]

\[ a_{n+1} = \text{FORGETTING - LOSING} + \text{WINNING} \]

WANDERING \rightarrow FIGHT \rightarrow WIN \rightarrow LOSE

\[ \text{NO/cGMP system} \]

\[ \text{CALMODULIN} \]

\[ \text{Ca}^2+ = \text{NOS} \]

\[ \text{O}_2 \rightarrow \text{X} \rightarrow \text{NO} \rightarrow \text{cGMP} \]

\[ \text{GTP} \]

\[ \text{ODQ} \]

\[ \text{L-NAME} \text{ (applied before 1st fighting bout)} \]

\[ \text{Dynamical Model} \]

\[ \text{INPUT} \rightarrow \text{NO} \rightarrow \text{cGMP} \rightarrow \text{OA} \rightarrow \text{BEHAVIOR SELECTION} \]

\[ \text{Amoeboid locomotion -} \]

\[ \text{ASIMO} \]

\[ \text{100\% morphological brain} \]

\[ \text{0\% computation} \]

\[ \text{FULLY ALGORITHMIC} \]

\[ \text{FULLY PASSIVE} \]

\[ \text{SLIME MOULD} \]

\[ \text{\# inhibition increased aggression in subordinates} \]

\[ \text{\# NO modulates neuronal activity of antennal lobe.} \]

\[ \text{\textit{multi-scale model}} \]

\[ \text{(common principle design)} \]

\[ \text{is this simply a trade-off?} \]
collective intelligence (no centralized control), "primitive" locomotion mode.
'SLIMEBOT' - 100 vs. 1000 units, move across topology towards goal light.
Slime mold can do this task. → adjusts shape according to motion underway, doesn't need to decide how to move every part of the body (collective).

**MECHANICAL STRUCTURE**

![Diagram of mechanical structure]

- Passive mode (high friction).
- Active mode (low friction).
- Switch between these modes; moves the slime in particular direction.
- Exploits "RHYTHMIC BEHAVIOR".
- "MUTUAL ENRAINTMENT" $\alpha = 1.0$ (oscillation in phase)

3) Degree of arm extension/contraction proportional.
Active mode propagates from head to tail.
Most cylindrical along phase gradient.

* Van der Pol oscillator
* Rhythmic, synchronized

1) Sensory feedback outer surface, $\alpha = 1.3$
    Goal light detected $\alpha = 0.7$
    Other, $\alpha = 1.0$

'Good deformation can be a good sensor.'

SLIME MOLD = example of ecologically-balanced coupling (close to PDW on ALGORITHMIC-PASSIVE scale)
PROGRAMMED JUMPING—brittle to disturbance.
Synergy by bi-articular muscles, angle is highly stable (MCKIBBEN muscles vs. several modes of locomotion during jumping (which creates lots of 6-7 drops out lateral forces). of a single cycle).

LOCOMOTION STABILITY at VARIANCE of JOINT STIFFNESS

CONTROLLER

* no-precise model
* network structure
* sensory feedback
* state reset

MUSCULO-SKELETAL SYSTEM

* visco-elastic
* back-drivability
* variable joint stiffness

JOINT-passivity (flexibility), antagonistic muscles.

RHYTHM GENERATOR (CCG) → ENTRAINMENT + JOINT STIFFNESS CONTROL

ARCH-SHAPED

STIFFNESS CONTROL

\[ P = 4.0 \times 10^{-7} t_p \]

\[ P = MPa \text{ (density)} \]

\[ t_p = \text{expiration time} \]

STABILITY

ADAPTABLE

HIGH STIFFNESS—walking

CHANGE STIFFNESS, gait transition?

VARIABLE STIFF—walk only

CHANGE STIFFNESS, unstable region
Morphological effects on stability/adaptability of locomotion.

**DAMPENING mechanism**

**ADAPTABILITY of pheromone tracking behavior of silkmoth revealed.**

**INSECT model** - apply adaptability of insects to robotics.

**ENVIRONMENT**

\[ \downarrow \text{ADAPTABILITY} \rightarrow \text{Behavior} \]

\[ \rightarrow \text{BODY (interchange w/robot)} \]

**ROBOT MODEL:** Emoto et al, 2007

- manipulate motor properties
- gain manipulation biased to one side (laterality)

- with vision 11/14
- w/o vision 4/14
  - comparable w/silkmoth behavior

**MALE SILKMOTH (Bombyx mori)**

- pheromone - source orientation
  - Kanazaki (1998)

\[ \text{STRAIGHT} \rightarrow \text{LOOP} \]

\[ \text{ZIGZAG TURNS} \]

**BUTTERFLY FLIGHT** - factors of stabilizing flight

- PANEL METHOD - unsteady flow created by flapping motion,
  - KINEMATICS
  - Flapping
  - Lead-lag
  - Abdomen

- Wake-induced flow - panel method w/wakes,
  - Vortices - search for periodic flight

**TURN ANGLE**

- Shift in orientation = Robot 'load' behavior

- Is this adaptability? What has changed in the brain?
Control dof in joints ($\theta_a, \beta, \rho, \Theta$) & initial condition of thorax ($z, \theta_p, x$) are searched → periodic 

**WAKES**  |  **NO WAKES**  

ALMOST PERIODIC  

$Y$  |  $\gamma$  

LYAPUNOV EXPONENT  |  EXPO

$17.1 > 1$  |  $8.6 > 1$  

unsteady wake-induced flow

FLIGHT w/ INITIAL PERTURBA.

(large instability)  |  (less instability)

For discrete-time system, optimal regulator is designed (quadratic criteria).

Repeated searched flapping motion w/ no control (unstable) chaotic?

STABLE FLIGHT → unstable semi-periodic trajectory might be stabilized by appropriate controllers.

**ADAPTIVE BIPEDAL LOCOMOTION** → phase resetting (adaptive mechanisms) → foot contact information reconstructed walking behavior (phase resetting inc. robustness).

Gluteus Max (GM)  |  IL

RHYTHM GENERATOR  |  PATTERN FORMATION

PHASE OSCILLATION  |  KINEMATIC DATA

MUSCULOSKELETAL SYSTEM

Phase resetting (timing of foot contact to toe-off) → perturbation (force, time) → force & foot contact, time v. toe-off.

Joint angles not affected, but GRFs are greatly modified by perturbation.
**BioMechanical simulation study of locomotion in Japanese monkey:**

- Locomotor neurophysiology
- Physical anthropology (human/primate evolution)

**QUADRUPED** → **TRANSITIONAL** (QUADRUPED/BIPED) → **BIPED** → **Skillful at bipedal locomotion after training.**

- Lordosis of lumbar spine (human-like)
- Inc. unjoint surface & long-bone strength
- Inc. inantigravity muscles
  - Longer stride
  - More extended hip, knee, & ankle joints
  - Sinusoidal motion of trunk
  - 2-peakd GRF profile (none)

CT-scan of body volume (derived inertial parameters)

Quadratic surface approximation (axis of rotation)
CADAVER for muscle parameters: whole-body musculoskeletal model.

3-D motion capture using 4 cameras.

**CEREBRAL CORTEX**

**BASAL GANGLIA**

**BRAINSTEM**

**CPG**

**DTF, VTF**

**VO**

**PERIPHERY**

2 global parameters:

\[ L = \text{length of limb axis} \]

\[ \Theta = \text{orientation of limb axis} \]

\( L, \Theta \) transformed into the motor commands (inverse kinematics) (high-gain PD control)

Neuro-control model in spinal cord is constructed.

**INSECT-MACHINE HYBRID SYSTEM**

Variety of sophisticated behavior

10^4-5 neurons

Moderate # of constituent neurons

Learning - modification of specific element of stereotyped behavior. Modification

**SENSORS**

**ENVIRON.**

**BODY**

* CROSS-SECTION # estimate of force \( \rightarrow \) 15-20% error from functional muscle

* Lack of 2 peaks in CHF range of motion at hip joint (vs. true biped) due to twisting geometry
1) IN Vivo Brain
2) Neuron Database
3) In Silico Brain
4) Model/Insect-Controlled Robot

Odor-Source Orientation:
- Behavioral Strategies
- Pheromone-Source Orientation
  - Only behavior for males.
  - Pheromone-triggered zigzag program
  - Reset mechanisms of programs


* Zigzag flying pattern 'reset' according to dynamics of plume

B) Neural mechanisms

Flip-Flop Neural activity
(state-dependent activity pattern) of VPC identified

La → Ra spikes alternate with pheromone stimulus

Mishima & Kanzaki (1999)
J. Comp. Phys A 189, 143

G-CaMP (transgene) part of 100 neurons identified

Antennal lobe [Nawiki & Kanzaki (2008)]
Frontiers in Neural Circuits

Mushroom body

Thoracic ganglion (discrete program)

Motor system for walking/flying is in thoracic ganglion

Abdominal ganglion

Thoracic ganglion

Antennal lobe

Mushroom body

Thoracic ganglion

Midline

MB

AL

LAL/VPc (premotor center)

Behavior (thoracic)

Mushroom body (learning memory)

Flap VPC
iAL descending neurons signal flip-flopping in motor systems (brief excitation/brief inhibition).

FLIP-FLOP → neck muscles, MNs involved in zigzag behavior,

LAL-Bilateral, LAL-local interneurons → identified more in Iwano (2008) J. Comp. Neurology than 100 neurons.

GABAergic (inhibitory) neurons → serotonergic, neutral activity

MODIFICATION OF BEHAVIORS - internal/external conditions -

* Serotonin regulates sensitivity to pheromone.

INPUT → CIRCADIAN

LEARN-MEM

SEROTONIN (5-HT)
NO (NITRIC OXIDE)

* Unique serotonin feedback neuron (in antenodal lobe).

* Pheromone habituation - evaluate adaptability of brain.

* compensation of unexpected sensory feedback

DIFFERENT ODORANT (LINALOOL) serotonergic control.
TRANSGENIC silkworm - pheromone receptor of different species → approach other species conspecifics, but SAKURAI & KANZAKI retain same behaviors, neuronal networks.

Could there be switching between motor programs? Anatomical areas involved w/ control?

ROBOTICS as TOOL for POSTURE & GAIT -

- energy efficiency
- stabilization

[UTILIZE DYNAMICS OF ROBOTIC SYSTEMS]

CPG outputs leg phase (stance/swing phase)

WALK ($F_o = 0.3$), $F_o = 0.5$ (TROT) → TEKKEN (large rolling motion w/o roll joint)

ROLL MOTION feedback to CPG

on natural ground w/ $F_o = 0.5$ (max)

\[ \text{LOW} \rightarrow \text{MED} \rightarrow \text{HIGH} \]

POSTURE CONTROL

HIGH \quad MID \quad LESS

SENS. FB \quad SENS. FB \quad SENS. FB

MOVEMENT

CPG (non-CPG spring-mass control oscillator) (oscillator) system

QUADRUPOD self-excited rhythmic motion

sensory info.

NON-OSCILLATORY TYPE CPG

Generation of adaptive gaits using leg-loading information.

HUMAN SPLIT BELT treadmill walking

PRE-FIXED BELT \quad ADAPTATION \quad POST-FIXED BELT

belt on left 2x faster than belt on right.
STABILIZATION OF FORWARD SPEED, POSTURE.

angular velocity control around contact point

TOUCHDOWN ANGLE CONTROL—
stepping reflex
small
Torque efficiency high
need small
foot

SIDEWAYS STEPPING—
2D biped (Tetsuro) → treadmill walking

constraint in sagittal plane, knee locked in stance phase

2 states in single step period— inverted pendulum

SWING LEG

STANCE LEG

'kicking'

by stance leg

angle velocity can be slow or large—affects gait/stability

DEFINITION OF STEP-TO-STRIKE LENGTH

Measure lift-off preadaptation
how much is it pulled off during split belt phase? P-gain

* step length of slow leg = large (P-gain),
* P-gain smaller post—adaptation
* step reflex (vestibulospinal reflex)
Cerebellum plays important role in muscle stiffness.

Cerebellar disease affects muscle gain.

Reactive control strategies integrate gait/posture using leg-loading information.


PNAS USA, 93, 13292-13297.

Reactive adaptations (inner mechanisms).

Predictive (conditioned responses).

Reisman (2005).


Acquiring info, under mechanical constraints:

Sensory abilities get degraded during fast movement.

Search vs. travel

(Explore) (reduce acquisition of sensory info.)

A. Albifrons - electrosensory due to EOD

Distortion in electrical field, impedance in medium (differential voltage between dipoles).

Ghostfish (following a plume)

Eyes & tail (dipole) are parallel.

Animal rotates into flow to follow plume, but loses resolution under fast movement (due to drag).
KNIFEFISH searching for prey: head is pitched above body (e.g. 30°).

Most of this is in strike phase.

ASAEDA, 2002 (visually-guided creatures).

Max. volume scanned per unit energy expended?

Back of body scans same fluid front of body already did.

Maximize volume by pitching body.

MODELING RIBBON FIN PROPULSION-

Immersed boundary method - area of volume occupied by body corrected for turbulence.

* Calculate forces over a biologically relevant range of motion parameters.

Optimizing sensory performance alone not possible due to energy, sensory, underactuation penalties.

Morphology & actuation → embodiment & sensorimotor performance.

Sort data by force (MN), highest thrust performance (also maximized in design of ribbon fin).

Morphology fits well for travel mode, problems arise in search mode (switch their locomotion posture).
AQUATIC NEUROBOTICS - Bioinspiration at small scales.

BIOLOGICAL SYSTEMS are just good enough 
but are robust & efficient.

NANOROBOTICS lab.
* Gecko adhesives
* Magnetic micro-robots
  - RSS/ICRA 2008

MAX. LIFT FORCE (mN)

\[ \text{surface tension} \quad \text{robotic insect} \quad dL^1 >> dL^3 \]

\[ \frac{\text{surface tension}}{\text{buoyancy}} \]

* Super-hydrodynamic legs (leg supports 15x body weight)
* Bending of legs reduces payload
* Maximize lift more w/ shorter & shorter legs.
* Infants scale / slide on H2O surface, adults jump on surface,
  Basilisk - robot model (water runner in pool).

AMOEBA during phagocytosis (cell as actuator).
PNAS, 102 (2005).
NATURE MATERIALS, 4.

Microbes really fast, always move.
Control reactants & propellants
Control speed of bacteria
Using switching paradigm

Gait control during transition (pond/land at end of pond) not understood, like search / travel / distinction.
ANTENNAL MECHANOSENS. CONTROL OF INSECT FLIGHT -

Giant red eye butterfly
MORENA & DANIEL, 2001
Manduka Sexta tracking oscillating flower (visual tracking of cue).

ANTENNAL POSITIONING RESP.

\[ \text{Antennal mechanosensor} \]

KLOPPENBERG, 1997

\[ \text{flagellum} \]

\[ \text{pedicel} \]

\[ \text{scape} \]

\[ \text{Johnston's organs} \]

\[ \text{Bohn's bristles} \]

\[ \text{DEVIATE FROM SET POINT} \rightarrow +/− \rightarrow \text{SENSORY} \]

\[ \text{MOTOR} \leftarrow \times \rightarrow +/− \]

BOHM'S BRISTLES - multiple axons project to antennal lobe, AMSE area, conserved across Lepidoptera.

AMSE also house MNs for antennal muscles.
Sensory arbors overlap w/ sensorimotor pathway

* Neurons tuned to 2x wingbeat frequency regime
  * Scoiopidal neurons tuned to Coriolis forces
  * unattach antennae from NS - backwards flight & collision (can fly but not orient).

MECHANICAL STIMULI - self-generated & external airflow, antennal vibrations

* mechanical stimulus experienced: at antenna, Coriolis forces
* what is encoded by basal sensors? mechanosensor
  * repeatable, robust response to mechanical vibrations in antenna.

ANTENNAL MOTION & SPIKE PATTERNS: phase lock at 50-60 Hz.
Chan-Dickinson Comp. Neurol., 1996

Knob at distal tip of antenna, enhances antenna (during gliding in flight)
Reafference principle → afferents from MNS play a role in this sensing.
Sawtooth-shaped course corrections.

Passive Pitch Reversal Flapping Wing
MAVs (Microfly, Microbat, DelFly II)
Target range (1-2 g, 5-10 cm).
Passive wing rotation → steering

Actuator & 4-Bar Wing Model
- Smoother trajectories.
- Delayed rotational lift peak.
- Similar translational & mean lift forces.

Neuromuscular Network
Somatic reflexes → well-balanced motion

Neuromuscular network - CNS & muscles - coordinated motion.
Muscle tension (musculoskeletal model)
Connect muscles, nerves using NN model.
Train using experimental data.

Determine connectivity
connection between
motor muscle spindles action & muscle
(use homuncular model).

MUSCULOSKELETAL model → forward / inverse kinematics

Neuromuscular net.
(MURALI, 2007)

Physiological data analyzed using ICA method.

Excitations regulate muscle contraction velocities.
Consider afferent/efferent signals in closed-loop system.

No clean mapping between
kinematics & muscle activation;
used mediating muscle spindle model to determine feedback.

Spasticity × efferents.

WATER RUNNER - lift generation on H2O + roll stability.
WATER interaction modeling - (lift & pull-out force).

BASILISKs - use fluid drag, not buoyancy.
Hydrodynamic / Hydrostatic forces.
directionally-compliant foot pad.
Pull-out force eventually exceeds lift force.
Possible unstable roll motion
(large roll moment of inertia $\rightarrow 4 \times 10^{-5}$ kg m$^2$)

System parameters $\rightarrow$ running freq, level (x lift force), roll moment of inertia.

ASSUMP #1 - interaction forces x tilted.

ASSUMP #2 - interaction force linear proportion to depth of footpad in water.

$\theta_i \leq \theta_f$ instantaneous angular acceleration makes system diverge.

RUN. FREQ. = 7-12 Hz

directionally compliant footpad $\rightarrow$ more stable, less angular acceleration.

why does robot use 4 feet while animal uses 2? Easier to control robot.

SLOTH KINEMATICS $\rightarrow$ FISCHER-BLICKHAN, 2006.

movements in parasagittal plane $\rightarrow$ proximal segments contribute to progression the most.

TRAVELING gait $\rightarrow$ EXPLORING gait
(diagonal coupling of limbs)

300 fps high-speed x-ray

HANDS & feet as rigid bones. First part of suspension phase - humeral retraction, second part - scapular retraction.

INFLUENCE OF GRAVITY

compressive forces on limbs
upright forces on limbs (flexors, counteract extensors)
suspensionary gait

tensile forces on limbs
Lateral movement of body, movement of scapular blade.

Forelimb segment displacements → compare to 8 species (FISHER, 2002)

Hand displacement is where kinematic difference is in locomotory variation across humans.

Exploratory-flexed forelimbs, lateral sequence

Traveling-extended " " trot-like.

* Scapular rotations contribute to propulsion in upright mammals.

Sloths cannot walk on ground, sprawl along vertical surface (due to suspensory adaptation) → only extant species in exploratory gait is really slow.

Extremely similar to branch-walking in primates (scapular movement phases).

** Body Stem & Extremities →

Inverted pendulum - spring-mass - skipping models

* Do not account for trunk undulation.
* Major feature of vertebrate locomotion.

Postural stability

1) Minimize head movements
2) Coordination of segments in body stem
3) Compensatory movements (head-trunk)


* Neuronal or non-neuronal control?
In evolution → morphology adapted to function

HANAVAN's MODEL

14 dof (viscoelastic elements)

1964 GFRS parameters

Dampen abdomen → thorax joint.

Compensatory movements → phase shift at joint

Compensatory mechanisms → motion dynamics → minimize neural control effort.

Variation of visco-elastic parameters → more morphological control (speaks to evolution).

Significant difference between males & females in body stem (not so much in legs). Affects gait parameters. Applications to spinal cord degeneration.

Neural control of insect walking - behavior of animals

Cellular → ion channels → neurons → neural networks → biomech/kinematics

Motor system only directly observation of brain/NS

BRAIN → ion channels → behavior

(signals prime execution of behavior - spinal cord, etc)
Vertebrates & invertebrates → similar motor infrastructure (despite vastly different brain architecture).

Kernels of networks → modules → neural control of segments

Neuronal locomotion - segments, muscles, groups, motor units (hierarchical organization)

Scaling - extend, reduce, size

CPGs $\rightarrow$ feedback - magnitude & timing modulation

CAT

STATE INSECT

feedback of movement activity, triggers phases of movement,

STANCE PHASE / POS. FEEDBACK

Length / load feedback → modulates movement

STANCE - SWING → unloading will inactivate muscle activity (stimulate right muscle, can prolong stance phase artificially).

LAMPREY → CPGs for segments & no cycle-to-cycle or leg joint coupling → at least 3 "CPGs"

STICK INSECT → one neuron (protraction-retraction signal)
Combination of foot leg stepping & local load info load increases — stance, load decreases — swing.

**Change:**
- Stepping velocity
- Walking speed (change cycle period — stance phase).

Single leg prep. → joint angle changes during stepping → intracellular recording → step faster → longer stance phase. (Like changing gain in different FB).

EMG of flexor → depolarization occurs later on, generating visually-guided turning behavior → optomotor stimulus + sticky surface, legs on left spin into drum, on right turn away from drum. (Pull into left turn).

**6-legged vs. 1-legged** → generation of turning movements (no difference between coordination & motion transfer, a single leg driven by neural control, w/o feedback).

Evolution: respiratory (short-phase coupling) → convert to walking (add decoupling for reflex information) by adding a level of modulation (add/remove gain).

Proprioceptors in leg counteract gravity -> vestibular system.


Long-lasting, context-dependent modification of stepping in the cat following repetitive stumbling correction reaction.

J. Neurophysiology, 97, 659-661.
PEARSON, K.G. (2003), SPINAL CORD INJURY REVEALS UNEXPECTED FUNCTION OF CUTANEOUS RECEPTORS, J. NEUROPHYSIOL, 90, 3583-3584.

No brain w/o body & vice versa.

BRAIN

BODY (MOTOR)

BODY (SENSORY)

ENVIRONMENT

BRAITENBERG (1984)

walking direction

control of individual leg

WALK NET (6 rules - interact between controllers)

swing

stance

Swing (3 joints)

Stance (18 joints)

*solutions for problems in control algorithm design.

*CRUSE, 1990, 1979, 1995 (Cruse rules)

PFEIFFER, 1992 (coordination - tetrapod legs - gait)

"Follow the leader" principle - (LPVF)

LOCAL POSITIVE VELOCITY FEEDBACK - sustain control of manipulators.

SCHNEIDER 2004, 2008

SCHMITT 2008

control of stance in a redundant system.

*Analytic solution *global controller, invariant geometry

*Change joints by angular velocity, amplitude, & direction (parameters for each joint).

Leave it to physics of interaction (local control approach).
Rhythmic movement of legs controlled by modular system exploits system dynamics (flip-flop). Extensive swing extension adaptation in stick insects. Slinky-like inertial forces & passive dynamics.

Circuit: swimming — walking in salamander walk to trot decerebrate cat, walk to fly in birds salamanders — lamprey & tetrapod research.

SWIMMING:
* traveling wave in axial muscles
  * tonic
  * shorter

WALKING:
* standing wave
  * link protactor phase control
  * longer cycle duration

Salamander robot (lamprey w/legs). INSPEERT, SCIENCE, 2007

1: lamprey-like body CPG + link CPG

H: strengths of coupling from limbs to body oscillators are strong

H: limb oscillators: lower intrinsic frequencies, cannot be higher

Bi:igger amplitude on one side (body oscillator) permits turning.

1. NEUROSCI. 23, G (2006)
2. CREPSI, ROBOTICS & AUTONOMOUS SYSTEMS.

1 → 2: two oscillators evolution to a phase-locked state
Saturation function → freq. & amplitude correlated, limited to specific frequency range

Limb oscillators actuate at a lower drive are slower than body oscillators.
STANDING WAVE in TROT → perfect synchrony in trunk
BODY LIMB coordination optimizes speed.
* RICHER motor skill & more
steady state behavior
* automatic transition, rapid inc, in freq. at transition.

1.6 - 3 Hz
STEMMING
0.6 - 1.2 Hz
STEPPING

IN EVOLUTION
* addition of
oscillatory centers w/diff. intrinsic & saturation frequencies (also add different types of gaits)

may make transitions unstable, but transition is smooth (slow down) in this case
Swimming on one side, walking on the other → chaotic  
+ drive on one side, - drive on the other (dampen transition)

sensory feedback — may enforce a standing wave on a traveling wave (adjust traveling waves during swimming).

BOSTON DYNAMICS (MARK RAIBERT)

HOMEOSTASES — pressures, sensors, flows
CONTROL —

LegLab robots — limitations
* flat terrain, offboard power, offboard computing, no payload, no real-world ruggedness

system doesn't tip forward or backward

WALKING — CLIMBING transition
* ground plane estimator, odometer angles

SUPPORT  BALANCE  POSTURE (move legs w/symmetry, keep body oscillation level)

NET FORCE
* MOMENT
  * LATERAL VELOCITY
  * HIP TORQUE
  * POSITION CONTROL
  * mass of legs (aids in correcting for lateral forces, instabilities)
Actuators cannot exert large forces across range of motion (like biological models), upper-bound on navigating rough terrain.

SLIP avoidance/differential (velocity of all legs move at same speed, kept that way by central control).

Biggest limitation is hip or shoulder range of motion. Self-righting → adding articulation to body of the robot.

Better reflex control than muscle power production (when challenged by rough terrain).

FOLLOW LEADER, FOLLOW PATH, CROSS-COUNTRY (proprioceptive senses deal w/small things, visual sensors deal w/big things).

MEMORY-DEPENDENT modification of stepping.

PDs ≠ high-powered actuation (passive-dynamics involve low force production generally).

Center of mass shifts slightly when adding on weight or when it engages steep terrain.

Dynamical Systems Approach for Movement Generation

* Develop bio-inspired architecture → non-linear dynamical systems for CPGs.
  * Limit cycles, fixed points (attractors)
  * Robustness against perturbation

Movement primitives (MPGs)

DISCRETE - goal-directed movement
RHYTHMIC - motion → amplitude/freq.
Quadrupedal locomotion on rough terrain
1) Postural control w/o locomotion
   (standing posture - balance, closed-loop control)
2) Reduce hip & knee joint values in one leg, increase in other leg (stilt morphology).

\[ U_t (\text{control}), X_i (\text{periodic movement}), Y_i (\text{discrete movement}) \]
\[ f(\phi) \text{ trajectories modulated by tilt.} \]

**POSTURAL CONTROL**
- Roll & Pitch
- Controlling locomotor direction
- Target & object acquisition -> visual module

**GOATDOG** -> 8 CPGs (hips/knees)

Spine servo twist:
\[ s = f(\phi) \]

* Target & obstacle avoidance / control
* Reflex reversal - biological mechanism -> different in stance & swing phase.

**ROLL/PITCH posture correction using an MPG**

**Dynamical systems** — global dynamics & robustness
- Always near an attractor, asymptotic stability
- (Quantify robustness?)

**SINGLE NEURAL PATHWAY -> COMPLEX BEHAVIOR**
- Visually-guided collision avoidance -> decision, guide motor behavior -> 40-50 MS
- Flight muscles
  - Right m97
  - Left m97

Output of circuit controls visual feedback generated by dome.

DOME SCREEN (VR system)
EMG - closed-loop feedback (Tucker Davis)
image subtends >10° on retina, avoidance response activated by animal.

Descending contralateral movement detector

as object gets closer, MNS fire more strongly.

DCMD encodes object size

Guest & Gray (2006) computation in pathway is sub-linear

Change trajectory of the target

more sensitive to small-field things

spikes/sec

time to collision

Object properties

flight motor firing rate (torques)

Closed-loop system

wing asymmetry

steering torques

stochastic properties of DCMD (spike timing) → may have bursting properties

better info in sensory systems w/bursting behavior (stochastic resonance vs. inc/dec firing rate)

Artificial Musculoskeletal System -

Explosive movement - tough task for a robot.


Pneumatic Muscles

high power/weight ratio, compliance
PNEUMATIC MUSCLE
(nonlinear spring, variable stiffness).

ANTAGONISTIC DRIVE → pressure control

TORQUE

MOTOR + gear reducer → CW/CCW transmission ratio.

BI-ARTICULAR MUSCLE,
FORCE OUTPUT = BANG-BANG control:
activate extensor muscle,
natural passive dynamics,
force profile.

\[ T = G_{TF}C(\theta) \]

\( G(\theta) \): Jacobian matrix

POSTURE CONTROL - PDE gain control

P - gain - small
I - gain - relatively high
Postural sway a natural feature of design.

COM, COP - sway similar to human.

Bio-inspired visuomotor convergence -
Optic flow (apparent visual motion = flow fields)

- Honeybee navigational heuristics → clutter response, centering response (optimize optical flow in tunnel setting).

Spatial perturbations - measure optic flow, regulate sine wave pattern.
angle (θ), asymmetry (y - a), distance (x)

lateral position
closeness to optimal optic flow (orientation)

Adaptive EMDs (parallel processing, temporal resolution)

motion detection
photoreceptors
tangential cells
descending pathway
MNs

robot w/ TANGENTIAL CELL
sensitivity = optic flow can make system much noisier = more adaptive.

what behaviors are achievable using simple model

TANGENTIAL CELLS are generalists, encode multiple parameters.

G-DOF

wide-field integration (spherical harmonics)
terrain following + centering response, robust means for achieving visual-based navigation.

Motion adaptation improve EMG coding of image velocity.
Modern control methods → neurophysiology, behavioral biology.

cerebral vs. visual system (or both)

ROBERT KIRSCHE → FES → control signal to evoke movement in high-spinal cord injury (C3 or above).
C1-C4 - paralysis in all muscles below neck. PE5; coordinated stimulation that restore movement functions.

Implanted stimulator, nerve cuffs, 4 EMG channels.

24 stimulation channels for arm/hand (all muscles in arm/hand)

Optimize muscle selection

* Preserve stability at shoulder.

* Musculoskeletal model

* Set maximum force to 0

* Each muscle will be activated to force more than 0, less than max. power of active muscle

* Simulate all combinations of possible stimulation.

* Use cuff electrode on certain nerves, multiple muscles at once

* Radial nerve → downstream from medial/lateral head of triceps → extensors

* Axillary, suprascapular nerves; Long thoracic nerves (place below certain branches, activates scapular muscles, stimulating all muscles that are associated w/a single nerve can make for sloppy movement.

* EMG electrode pairs, act on active muscles to stimulate atrophied muscles.
Tell arm what they want to do
- conventional techniques (mech/face EMG, voice recognition, BMI's, head orientation).
- real-time modeling, VR-based feedback.
- muscle selection simulations
- forward simulations in real-time (ability to control virtual arm).

Feedback control -
- reduce cognitive burden as dof increase
- mouse control of 2-D cursor using head orientation & EMG \rightarrow speed/performance measures
- train muscle out of state of atrophy recapture muscle power.

BRAIN

\[ \text{EXTERNAL CONTROLLER} \rightarrow \text{SIMULATED FES} \rightarrow \text{MUSCULOSKELETAL MODEL} \rightarrow \text{ARM CONTROL} \]

FB CONTROL OF ARM MOVEMENTS:
- REF. TRAJECTORY \rightarrow \text{INVERSE MODEL ANN} \rightarrow \text{MODEL}
- PIO \rightarrow \text{STEADY-STATE ANN (nonlinearities)}
- Revised trajectories

Humans can't control
2 EMG signals simultaneously (proprioceptive limits) \rightarrow
trace looks rectangular.
First control one muscle, then the other.

Surface stimulation (can't activate all muscles directly)
- hyperreflexia, spasticity can affect how movements are recovered (smooth, etc)

\# Signals mapped to kinematics, velocity.
BRUNNER → unit burst generator (1981).

- Rhythmic excitation, inhibition; tonic excitation, spike excitation all converge
- Prematurely initiate swing phase → depolarizing interneurons (controls joints).

**TAKE-HOME MESSAGE**

- Load feedback (global action, sparse connectivity to all CPGs).

Numerous feedback pathways converge of specific CPG populations

- Presynaptic afferent interaction
- Modified weighting of parallel pathways

INTERSEGMENTAL COORDINATION → behavioral rules between limbs (tripod/tetrapod in insects). 6 rules that determine interaction, gait:

- Stepping (front leg), coordinates activity in caudal CPGs
- \[ \text{Caudal segments} \] record in caudal segments.