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Workshop on Walking Machines, Bielefeld, Jul.4 2003

Adaptive Motion Integration of a Quadruped Robot based on Dynamics and Biological Concept

Hiroshi Kimura
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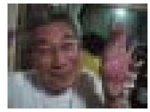
Tokyo, Japan

2

History of Legged Locomotion Study in Japan (never told)

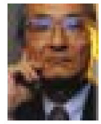
Prof. Miura



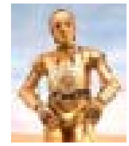
Because I'm a romanticist!

Why do you study on legged robots?

1987 Which is better as the future service robot?



Prof. Inoue



3

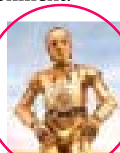
History of Legged Locomotion Study in Japan (never told)

[from old Chinese proverb]

Emperor easily changes his mind!

1990' Humanoid is good for working in the human environment.

Prof. Inoue



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Outline

- Why we can/should learn from animals
- Common principles in robots and animals
- Applying biological concepts to a quadruped robot
- Stability and energy consumption
- Discussions
- Summary

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Recent Popular Legged Robots in Japan

Self-contained!

Adaptive?

Just following the pre-programmed motion pattern

Legged Locomotion on Irregular Terrain

Conventional Method
- precise model
- trajectory planning
- control

variety of irregularity

Problem
Autonomous Adaptation

?

How we can learn from animals

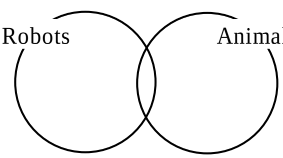
~~Functions of Animals → (mimicking) → Robots~~

Functions of Animals → (analysis) → Principles → Robots

Hypothesis on Legged Locomotion
- principles of mechanism and motion -

low speed motion

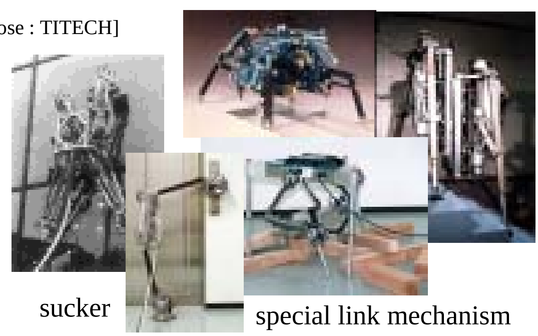
Robots Animals



A lot of alternatives
in mechanism, devices
and control methods

Examples of Not Mimicking Animals

[Hirose : TITECH]



sucker

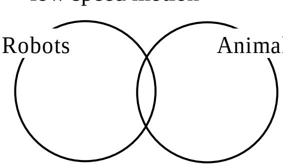
wheel-leg

special link mechanism
pantograph, parallel, ….

Hypothesis on Legged Locomotion
- principles of mechanism and motion -

low speed motion

Robots Animals



A lot of alternatives
in mechanism, devices
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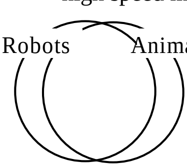
high speed motion

Robots Animals



Only few alternatives
since dynamics is dominant

The differences
in the number of joints and actuators, etc.
become not so important.

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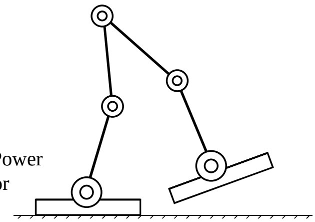
Not Good Mechanical Design

Energy consumption : Large

Adaptability to irregular terrain : Small

independent of the number of legs

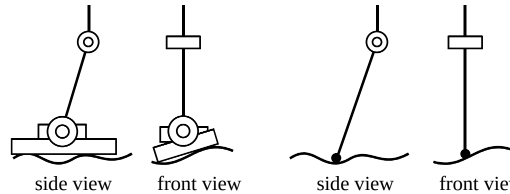


Large Power Actuator

⇩

Large Foot

"Size of Foot" vs. "Adaptability to Irregular Terrain"



⇧

Influence of local shape of terrain : large

Not Good Mechanical Design

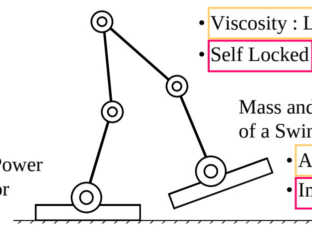
Energy consumption : Large

Adaptability to irregular terrain : Small

independent of the number of legs

Gear Reduction Ratio : High

- Viscosity : Large
- Self Locked



Mass and Inertia Moment of a Swinging Leg : Large

- Ac/Deceleration Torque
- Impact Force at Landing

Large Power Actuator

⇩

Large Foot

High Gain Feedback at the Swinging Leg Joints

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Control Methods According to the Speed

[Blickhan & Full:1993], [Full & Koditschek:1999]

	ZMP-based	Limit-Cycle-based	
		Neural System	Musculoskeletal System
good for control of	posture	low / medium speed walking	high speed running
main controller	upper neural system (learning)	lower neural system (CPG + reflexes)	visco-elasticity of muscles (self stabilization)

role of sensor feedback: large ⟷ small

Why the role of sensor feedback becomes small in high speed locomotion?

- Kinetic energy is large and dominant.
- In the short cyclic period,
  - the influence of actuator output is small, problem!
  - motion cannot be stabilized by the direct actuation.
- In the short cyclic period,
  - the accumulation of errors is small, advantage!
  - motion can be stabilized by the exchange of stance/swing phases.

    non-linear switching control

Stabilization of Forward Speed

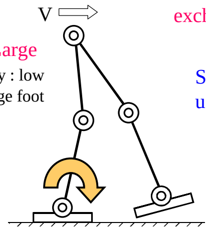
independent of the number of legs

Angular Velocity Control around contact point	Touchdown Angle Control
by ankle joint torque, control the angular velocity of the supporting leg	by touchdown angle, control the forward speed of the next stance phase

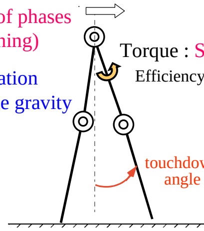
exchange of phases (switching)

Stabilization using the gravity

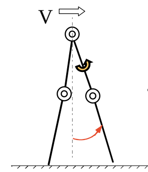
Torque : Large
Efficiency : low
Needs large foot



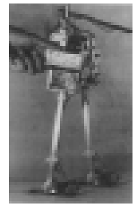
Torque : Small
Efficiency : high



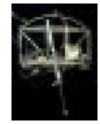
Stabilization of Forward Speed - Touchdown Angle Control -



in biological system
stepping reflex



Biper3
Miura & Shimoyama
[IJRR:1984]

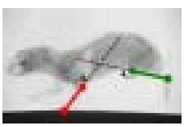


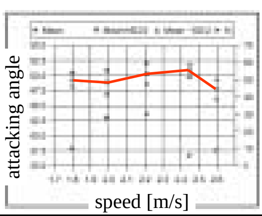
Raibert:1984
the neutral-point foot-placement algorithm

……

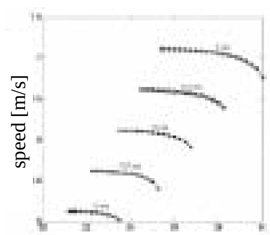
Touchdown (Attacking) Angle in Running

[Hackert, Witte & Fischer : AMAM2000]





[Buehler, et al. : AMAM2003]



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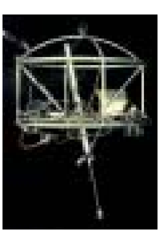
Hopping Robots

by Raibert [1983-1992]

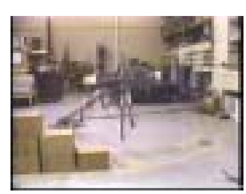


- Point contact
- Air spring
- Light weight leg and the body of large inertia moment
- Touchdown angle control, others

Hopping Robots

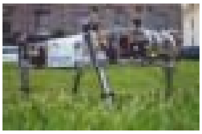
Touchdown angle control

by Raibert [1983-1992]



Running on irregular terrain

Quadruped & Hexapod Robots



[SCOUT-II]

[RHex]

[Sprawlita]

- Point contact
- (Passive) compliant and light weight leg
- Analysis of self stabilization

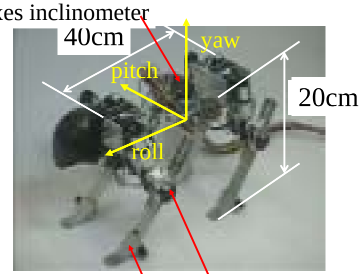
Quadruped Robot: 'Tekken'

- Weight:3.1Kg

2 axes rate gyro &
2 axes inclinometer

- Pitch Axis (3 joints)
  - Hip & Knee joints: active
  - Ankle joint: passive
- Yaw Axis (1 joint)

- Light weight leg
- Small foot
- Small gear ratio: ~16
  - viscosity: small
  - compliant joint



contact sensor

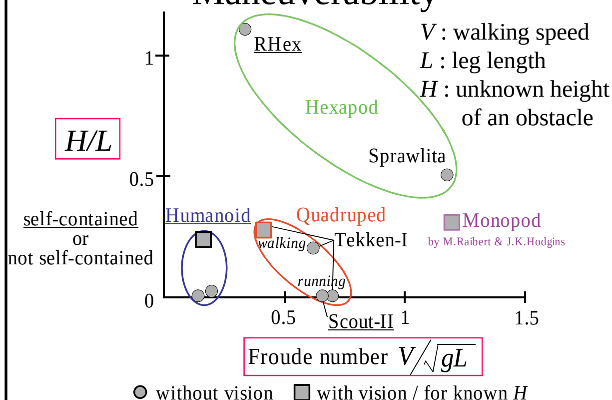
encoder

Sensor based adaptive walking on irregular terrain

Over Obstacles and Slopes

Maneuverability

V : walking speed
L : leg length
H : unknown height of an obstacle



Characteristics of Legged Robots based on Dynamics and Biological Concepts

- Mechanical design good for
  - medium & high speed locomotion
  - adaptation to irregular terrain
- Short cyclic period : rhythmic motion
- Complicated trajectory planning and control are not necessary.

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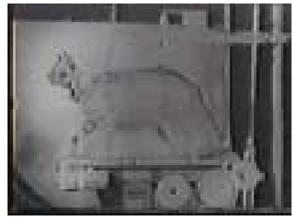
Decerebrate Cat

……………………..

[Brown:1939]



[Shik & Orlovsky:1960']

……………………..

The center of generation and adaptation of locomotion is located at the spinal cord.

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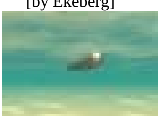
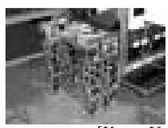
Locomotion Control Using Neural System Model

[by Ekeberg]



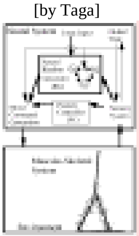
[Northeastern Univ.]

BISAM



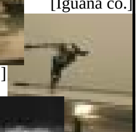
[Kyoto Univ.]

[by Taga]



Patrush[UEC]

[Iguana co.]



[TU-Munich]

Tarry-II

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What is Neural System Model Control?

- Rhythm
- Phase Difference between Legs

CPGs

- Tuning of Muscle Tone

Reflexes

Physiological Experiments Using Cats :

……….

S. Mori [1973]

……….

Computer Simulation & Robot Experiments

………………

Kimura [1994-]

………………

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Tuning of Muscle Tone

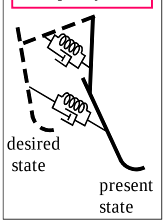
Joint PD Control as a Tonic Stretch Reflex

$$trq_{jnt} = -K1_{jnt}\,(\theta^*_{jnt} - \theta_{jnt}) - K2\,\dot{\theta}_{jnt}$$

$$\theta^*_{jnt} = \begin{cases} \theta^{stance}_{jnt} \\ \theta^{swing}_{jnt} \end{cases}$$

$$K1_{jnt} = \begin{cases} K1^{stance}_{jnt} \\ K1^{swing}_{jnt} \end{cases}$$

virtual spring-damper system



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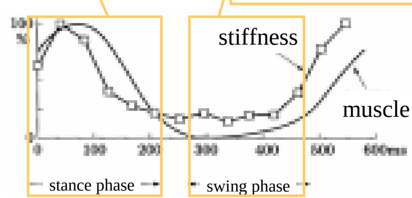
Change of Stiffness in Stance/Swing Phases

Tekken[2001-] & Collie-2[1987]

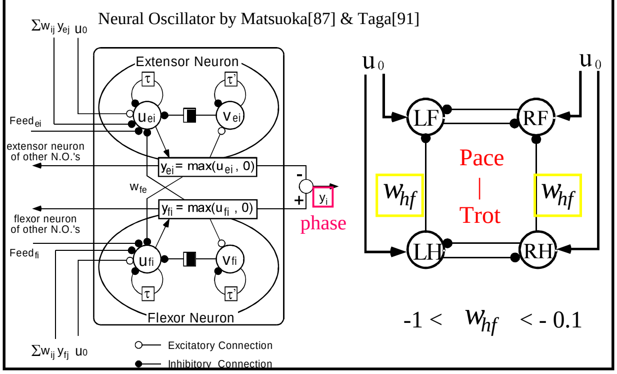
large in the stance phase
- against the gravity

small in the swing phase
- for irregular terrain
- reduce the impact force



Muscle tone and stiffness of walking cats [Akazawa:1982]

CPG (Central Pattern Generator)



Neural Oscillator

Matsuoka[87], Taga[91]

time constant

$$\tau \dot{u}_{\{e,f\}i} = -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} + u_{0i} + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_j$$

$$y_{\{e,f\}i} = \max(0, u_{\{e,f\}i})$$

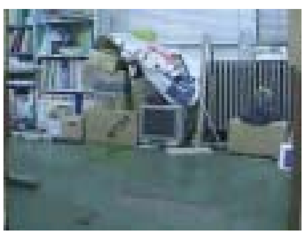
$$\tau' \dot{v}_{\{e,f\}i} = -v_{\{e,f\}i} + y_{\{e,f\}i}$$

joint angle, body roll angle, etc.

$u_{\{e,f\}i}$: inner state of the neuron $y_{\{e,f\}i}$: output of the neuron

$v_{\{e,f\}i}$: variable representing the self inhibition

Gaits

Trot: *v = 0.6m/s, T = 0.35s* Walk: *v = 0.3m/s, T = 0.6s*

-0.7 ← w_{hf} → -0.3

Other Mobility


Running in a bound gait Changing the direction

Motion Generation & Adaptation

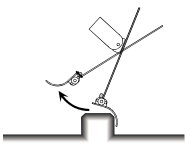
- Tuning of Muscle Tone
  - •torque output
  - •sensory feedback → reflex
- Rhythm Generation (CPG: Central Pattern Generator)
  - •phase (stance/swing) output
  - •sensory feedback → response

Motion Adaptation & Sensory Feedback

[Tekken:2001]

■ the legs should be free to move forward during the first period of the swing phase, Passive ankle joint & Flexor reflex

Passive Ankle & Flexor Reflex



- spring and lock mechanism
- contact & collision detect sensor

Over an obstacle
2.0cm in height

Motion Adaptation & Sensory Feedback

[Tekken:2001]

- the legs should be free to move forward during the first period of the swing phase, — Passive ankle joint & Flexor reflex

- the legs should land reliably on the ground during the second period of the swing phase, — Tonic labyrinthine response for rolling
- the phase difference between rolling motion of the body and pitching motion of legs should be maintained,

Stepping reflex & Vestibulospinal reflex/response for pitching
- the average of the forward speed be kept constant,

Vestibulospinal reflex/response for pitching

Slope of 10 degree inclination

Motion Adaptation & Sensory Feedback

[Tekken:2001]

- the legs should be free to move forward during the first period of the swing phase, — Passive ankle joint & Flexor reflex

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- the phase difference between rolling motion of the body and pitching motion of legs should be maintained,

Stepping reflex & Vestibulospinal reflex/response for pitching
- the average of the forward speed be kept constant,

CPG network
- phase difference between legs be kept appropriately.

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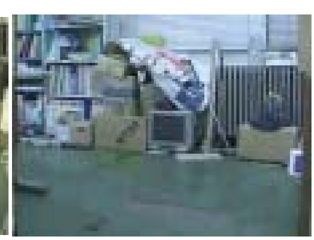
Waking in a long cyclic period is difficult to stabilize.



Trot *T = 0.35s*, *easy* Walk *T = 0.6s*, *difficult*

Large rolling motion naturally generated disturbs pitching motion. → Rolling motion feedback to CPG

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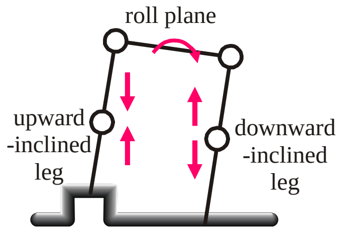
Nanzando's Medical Dic. 18th edn.

Tonic Labyrinthine Reflex for Rolling or Vestibular Reflex

Principles of Neuro Science, 3rd edn.



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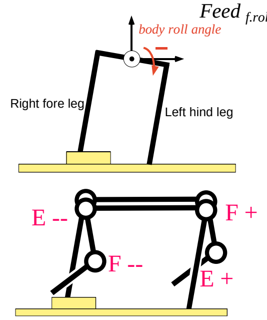
Roll Motion Feedback to CPG

$$Feed_{e.roll} = \delta(leg) \times k_{roll} \times \underline{(body\ roll\ angle)} < 0$$

$$Feed_{f.roll} = - Feed_{e.roll}$$



Right fore leg	E -- / F +	Right hind leg	E -- / F +
Left fore leg	E + / F --	Left Hind leg	E + / F --

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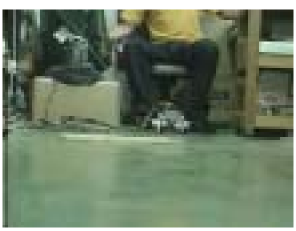
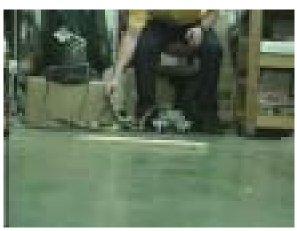
Roll Motion Feedback to CPG

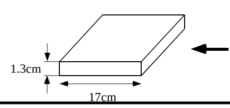




Without

With

T = 0.3 sec.



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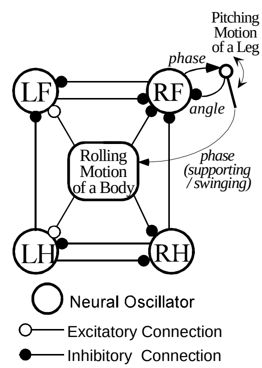
Rolling Motion as Standard of Rhythm



Rolling motion feedback to CPG

↓

Stabilizing a gait

Adjusting phases of CPGs

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Roll Motion Feedback to CPG

Slope of 5 & 3 degree inclination

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Over an Obstacle of 20% Relative Height to a Leg

Over an obstacle 4.0cm in height

Walking over Pebbles

Walking over Pebbles

slow motion replay

The values of all parameters are fixed for unknown terrain of medium degree of irregularity.

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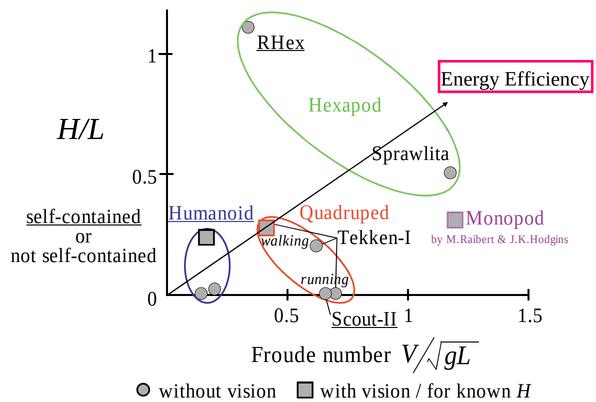
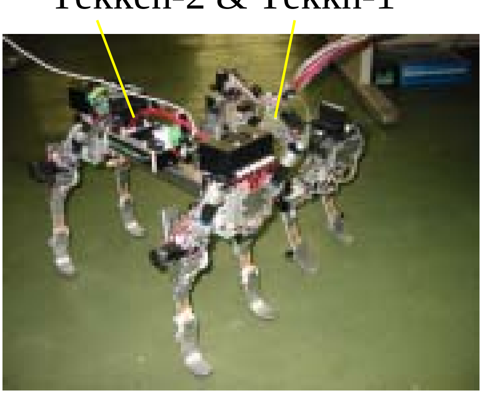
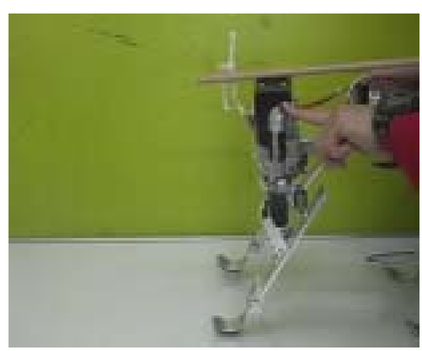
Maneuverability



Tekken-2 & Tekkn-1



Mechanically Variable Stiffness of Knee Joints



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Tekken-2

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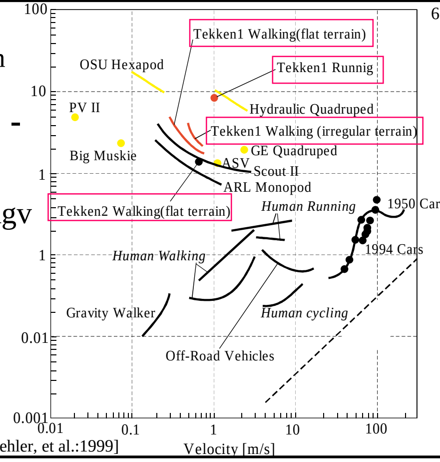
Energy Consumption

-

$\varepsilon = P/mgv$



modified from [Buehler, et al.:1999]

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How to solve the trade off problem between stability & energy consumption

Small τ increases stability, but also energy consumption

Change τ according to the irregularity of terrain:

Flat terrain → Large τ

Irregular terrain → Small τ

Visual Adaptation

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Outline

- Why we can/should learn from animals
- Common principles in robots and animals
- Applying biological concepts to a quadruped robot
- Stability and energy consumption
- Discussions
- Summary

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Discussion #1

What is Neural System Model Control?

ZMP Based

Limit Cycle Based

Equivalent?

CPG (Central Pattern Generator)

Interaction

Reflexes

Real Mechanism?

Feedforward
compensation of gravity and inertia force

Feedback
correction of errors using sensor information

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Discussion #1

Motion Generation & Adaptation

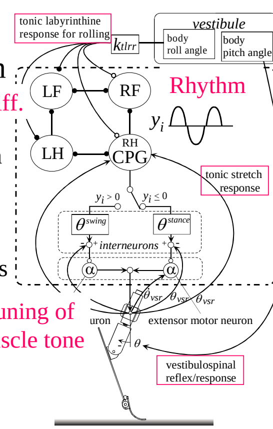
Phase diff.

CPG outputs phase information (stance/swing phase).

Hip joint angle, the body pitch and roll angle are input to CPGs as responses.

PD controller outputs joint torque as reflexes.

Tuning of muscle tone



Discussion #2

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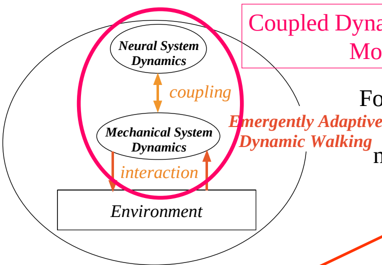
Autonomous Adaptive Walking

by Taga[1991]

Coupled Dynamic based Motion Generation



For desirable adaptation, we must construct neural system carefully.

dynamic walking on irregular terrain

physics,
biology,
physiology,
…

Discussion #2

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How dynamics of mechanism is encoded into parameters of the neural system

- Relation between the leg length and the time constant of CPG!
  - Choose the original cyclic period of CPG as

$$T_{CPG}^{\,O} \propto \sqrt{length\ of\ a\ leg}$$

- Reflexes / Responses ?

Discussion #3

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CPG Models

Cruse , Ekeberg
- •more sensor dependent & more decentralized
- •more general
- •cyclic period is determined by speed of the body and legs

Taga, Kimura, Ilg, Tsujita&Tsuchiya, Lewis, …
- •non-linear oscillator
- •time constant or standard cyclic period
- •dynamics of mechanism is encoded into parameters of the neural system

argument (BC:2002)

essential for dynamic walking by Kimura (IJRR2003)

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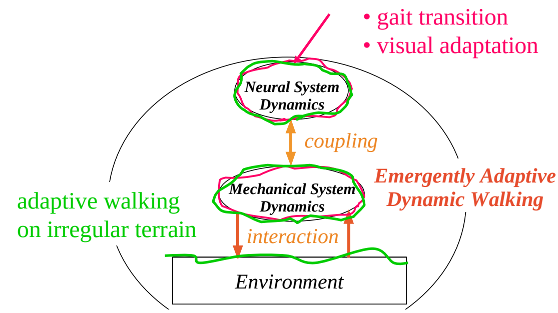
Coupled Dynamics based Motion Generation

- gait transition
- visual adaptation



Emergently Adaptive Dynamic Walking

adaptive walking on irregular terrain

autonomous adaptation at levels from the lower spring-damper system to the higher vision system

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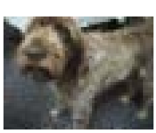
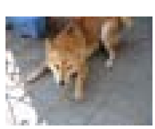
Future Works

- Self-contained System & Outdoor Experiments
- Visual Adaptation
- Behavior
- Bipedal Locomotion


[of Prof. Fischer]


[of Kimura]

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Behavior and Tuning of Muscle Tone


[S. Mori:1996]


[Prochazka:1988]

Future Works

- Self-contained System & Outdoor Experiments
- Visual Adaptation
- Behavior
- Bipedal Locomotion

Johnnie

Bipedal Locomotion of Japanese Monkey

[F. Mori & S. Mori : 2003]

END

http://www.kimura.is.uec.ac.jp

Thank all of you who impressed me.