Biologically Inspired
Adaptive Dynamic Walking
of the Quadruped on Irregular Terrain

Hiroshi Kimura
Univ. of Electro-Communications,
Tokyo, Japan

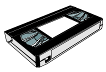
CONTENTS

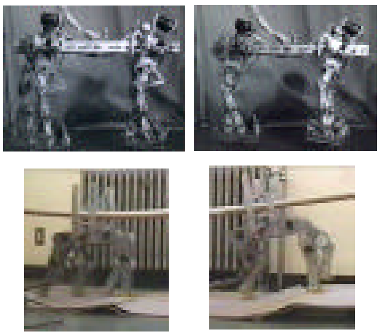
Previous Studies

Dynamic Walking amd Running on Irregular Terrain

- Monopod
  - [Raibert:91]
- Biped
  - [Takanishi:94], [Kajita:96], [Pratt:98]
- Quadruped
  - [Hirose:94], [Buehler:98]

Dynamics-Based vs Biologically Inspired





optimization

adaptation

Previous Studies

Biologically Inspired Control

- Insect
  - Hexapod [Beer:91], [Pfeiffer:94]
- Vertebrate
  - simulation
    - Biped [Taga:91,95], [Yamasaki:98]
    - Lamprey&Salamander [Lewis:96], [Ijspeert:98]
  - robot
    - Quadruped [Kimura:95,97], [Dillmann:99]

Dynamic Walking on Irregular Terrain

Conventional Method: precise model, trajectory planning & control

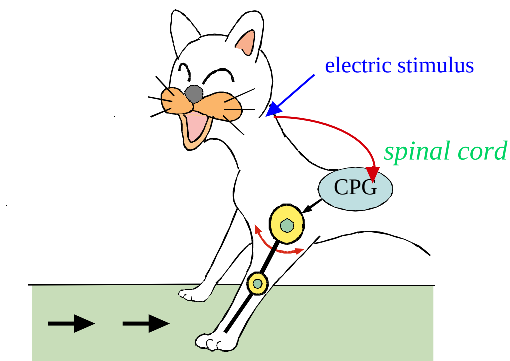
→ *variety of irregularity* →

Problem: autonomous adaptation

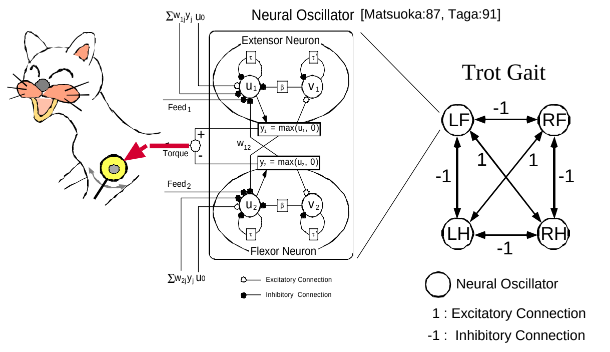
→ *biology, physiology, ...* →

Biologically Inspired Method

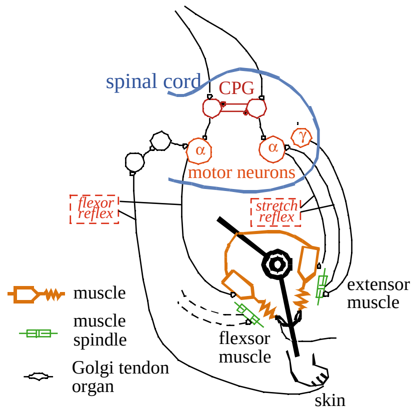
Stimulus for Starting Walking Motion



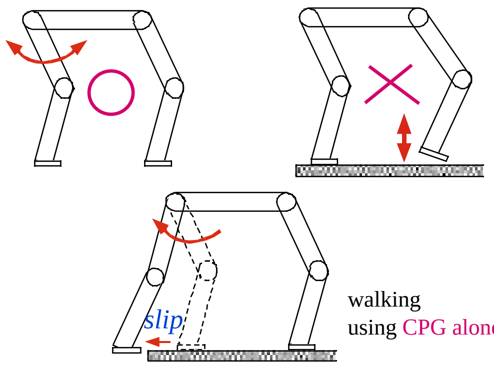
CPG (Central Pattern Generator)



Lower Nervous System of Legged Locomotion in Animals

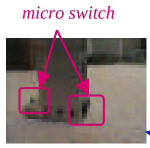


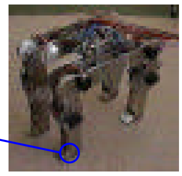
CPG is nothing but a Rhythm Generator



walking
using CPG alone

Quadruped Robot

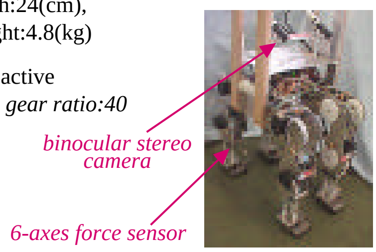




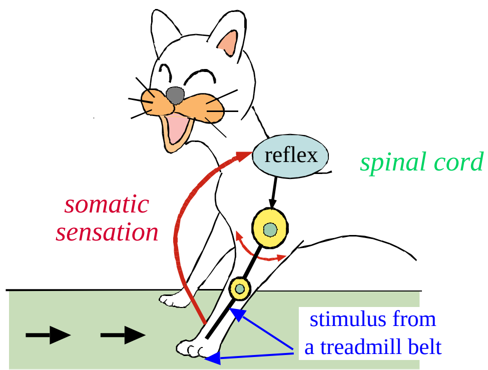
length:36(cm), width:24(cm),
height:33(cm), weight:4.8(kg)

hip and knee joints: active
DC motor:23(W), gear ratio:40

ankle joint: passive

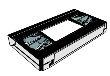


Stimulus for Starting Walking Motion



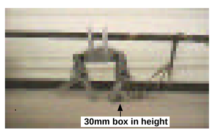
Video

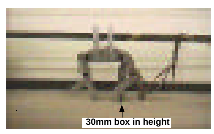
1. Walking on Flat Floor
2. Walking with a Swinging Leg Obstructed



(2-1) not using the flexor reflex ⟶ fail

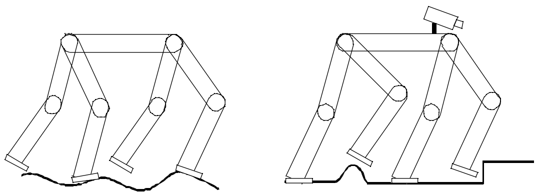
(2-2) using the flexor reflex





3. Running with Spring Mechanisms

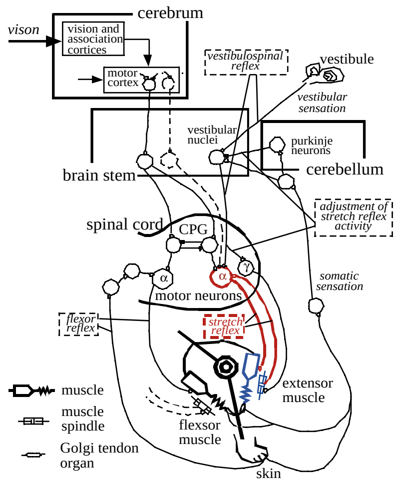
Terrain of Middle Degree Irregularity



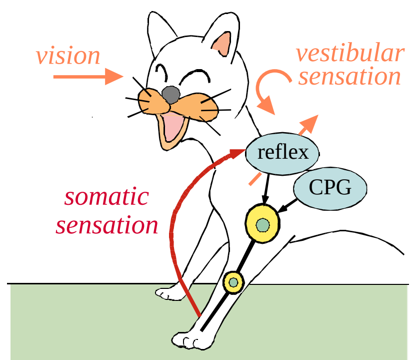
undulation

obstacle and step

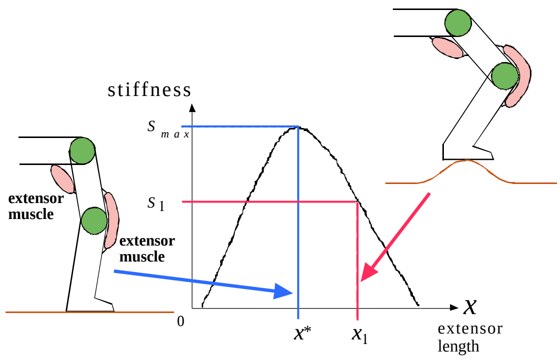
Muscle Stiffness Model



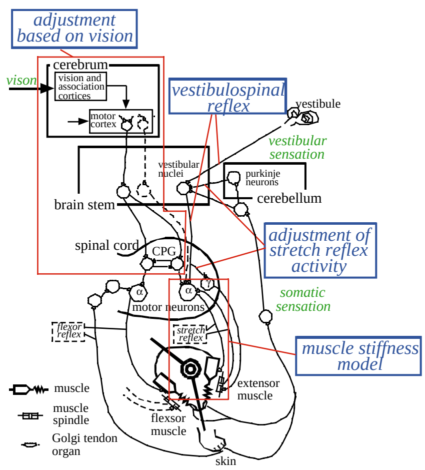
Adaptive Control Mechanism in Animal



Muscle Stiffness Model

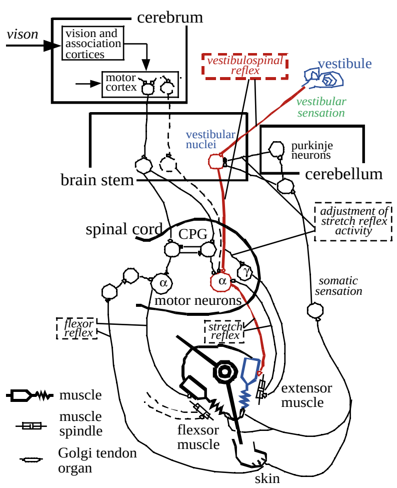


Nervous System of Legged Locomotion in Animals



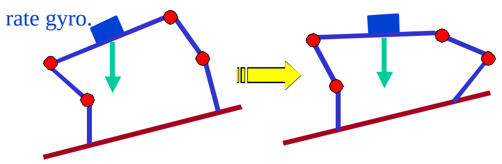
Four Adaptive Control Mechanisms

Vestibulospinal Reflex

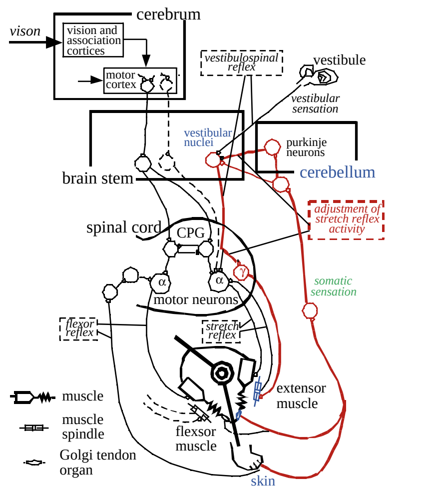


Vestibulospinal Reflex

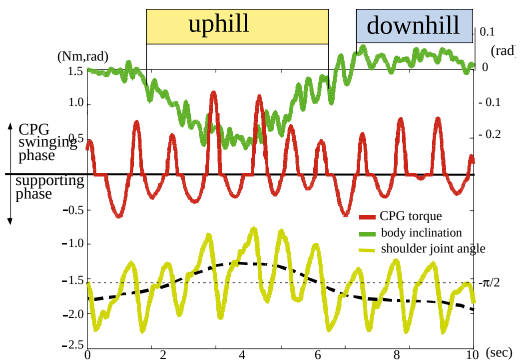
Inclination of a body → Bend knee joints of forelegs



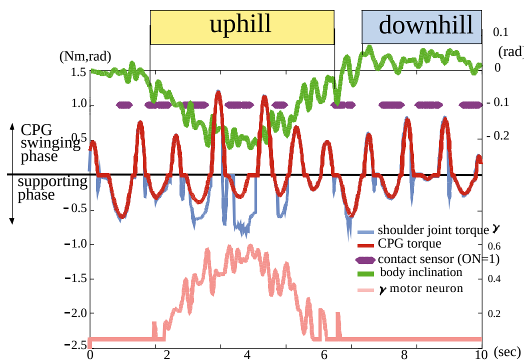
Adjustment of Stretch Reflex Activity



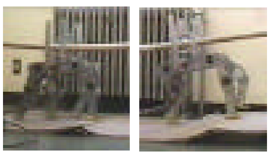
Vestibulospinal Reflex

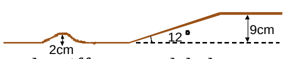


Adjustment of Stretch Relfex Activity

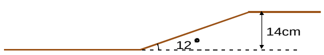


Video



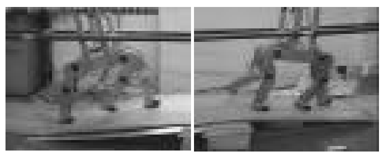


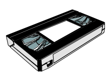
1. muscle stiffness model alone → fail
2. muscle stiffness model & vestibulospinal reflex

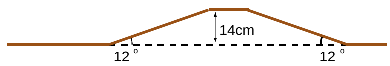


3. muscle stiffness model & vestibulospinal reflex → fail

Video



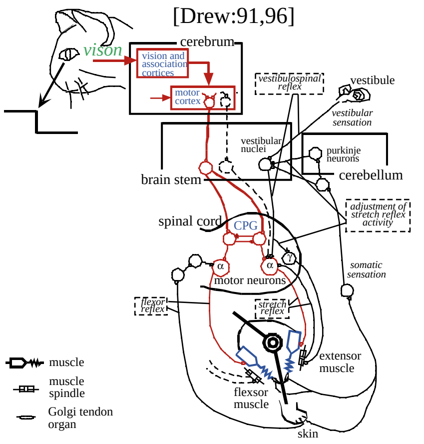




4. muscle stiffness model & vestibulospinal reflex & adjustment of stretch reflex activity

Adjustment of External Inputs to CPG based on Vision

[Drew:91,96]



Video

5. Walking up a step 3cm in height

(5-1) with constant external input ⟶ fail

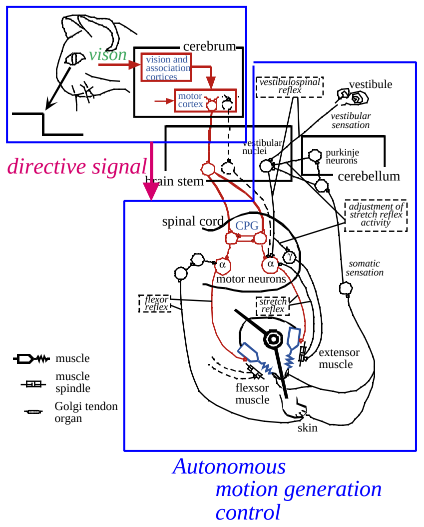
(5-2) by increasing external input using vision

When and how much should the external input to CPG be increased for the recognized step?

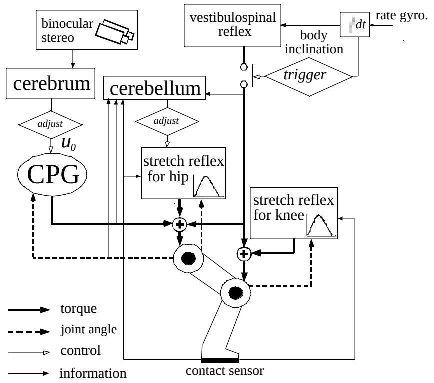
↓

Learning

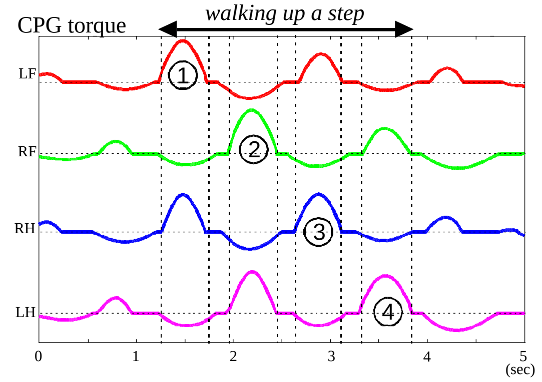
Hierarchical System



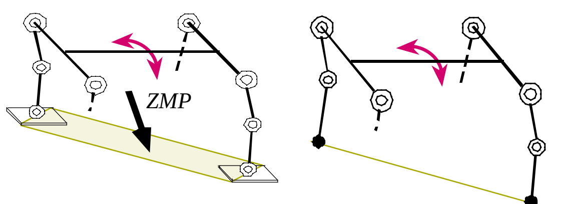
Actual Control Diagram of a Leg



Adjustment of the External Input to CPG



ZMP based vs. Inverted Pendulum based

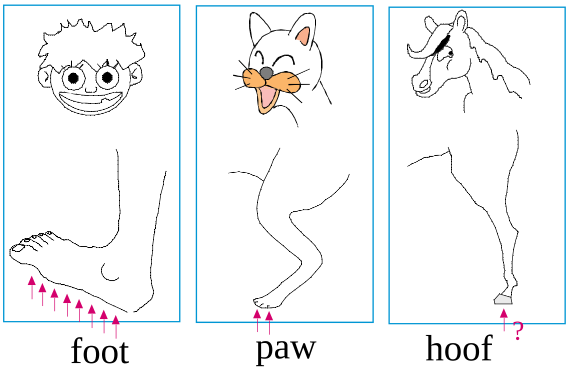


ZMP (Zero Moment Point)

↕

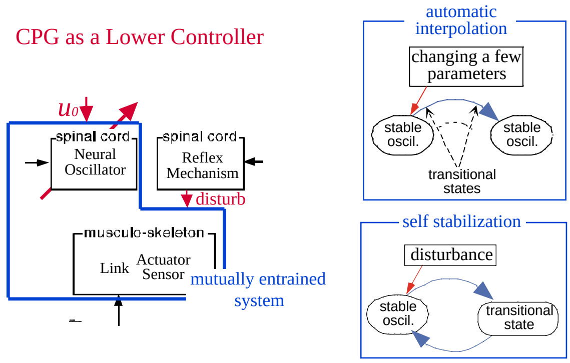
CPG based

Is ZMP detectable ?



Advantages of Biologically Inspired Control #1

CPG as a Lower Controller



Which is primitive ?

Static (or Dynamic) Walking based on ZMP

position control of ZMP

model

trajectory based

↔

Dynamic Walking based on Inverted Pendulum

limit cycle on a phase plane

Dynamic Walking using CPG + Reflexes

no model

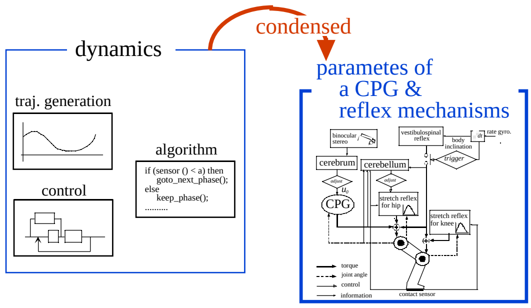
torque based

no passive static walking — passive dynamic walking

acquired by learning — genetically programmed

Advantages of Biologically Inspired Control #2

Parameterization → *optimization, learning*

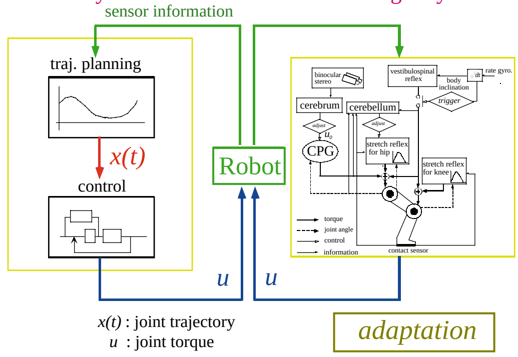


Correspondence

Biology	*Robotics*
CPG	*limit cycle*
	inertia torque compensation by feedforward
stretch reflex	*feedback control*
muscle stiffness model	*compliance control*
vestibulospinal reflex	*attitude control with rate-gyro*
cerebellum adaptation learning	*adaptive control* *learning control*

Advantages of Biologically Inspired Control #3

Dual System vs. Single System

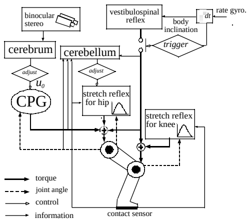


Objections ?

Can we forecast what happens?

Mechanical design?

No theory?



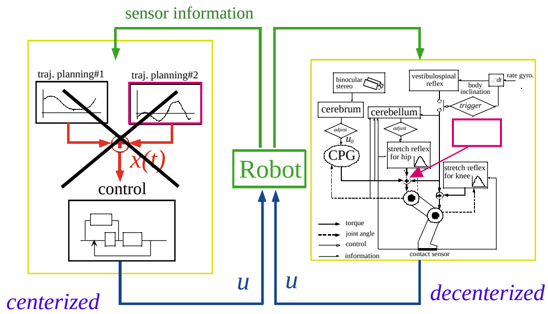
What is made clear.

- Rhythmic motion ← CPG
- To deal with interaction with environment ← Reflexes
- Changing few parameters of CPG and Reflexes

→ Adaptive Dynamic Walking on Irregular Terrain

Consistency in Adding a New Function

Dual System vs. Single System



x(t) : joint trajectory
u : joint torque

Future Works

- Fine Sensors for Somatic Sensation

  force sensor, distributed contact sensor, etc.

- 3D Walking on 3D Irregular Terrain
- More Adaptative Control & Learning
  - *basal ganglia*
  - *cerebellum*

Legged Locomotion Studies in Robotics

various aspects

- to develop a practical walking machine
- to clarify a real nature of legged locomotion by
  - analysis of passive dynamic walking and hopping
  - realization of dynamic walking and running by simplified control

in view of dynamic adaptation to irregular terrain

→ realization of adaptive dynamic walking by simplified control