Walking and Running of a Quadruped Robot on Irregular Terrain

- The State of Art in Legged Locomotion Study -

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Tekken4
- 32 times Demo
- 3 times TV
- 17,000 people / day

House keeping dog in a garden (rush to the thief and take a picture)
Outlines

• Legged locomotion control methods
• Legged robots based on biological concepts
• Emergingly adaptive walking study
• Adaptive walking of a quadruped robot
• Adaptive running of a quadruped robot
• Summary & Others
Recent Popular Legged Robots in Japan

Self-contained!

Adaptive?

Just following the pre-programmed motion pattern
What is legged locomotion?

Manipulation of a Body

Stabilization of Non-linear Oscillation

dynamic walking  hopping  juggling
ZMP Based vs. Limit Cycle Based

Zero Moment Point

Stable Limit Cycle on Phase Plane
ZMP Based

In order to avoid falling down, realize the given trajectory as precise as possible.

Control of a arm
ZMP-based
Motion Generation and Control

Limit Cycle Based

To keep the stable oscillation,

Switching stance/swing phases → non-linearity

swing phase

Phase plane

stance phase
Limit Cycle based Motion Control

TomCat [Jul. 2003]

the upper bound of the cyclic period of walking
Passive Dynamic Walking

A walking machine can walk down the slope without actuation.

Is the control necessary?

(Cornel Univ : 2000)
Adaptive Oscillation
- Self-excited or Enforced -

- self-excited oscillation
  - ex. swinging game
- enforced oscillation + synchronization

Self-excited Walking of Planar Biped


\[ T = -k\theta_3 \]

Hip joint torque  Knee joint angle

self-excited oscillation only by sensor feedback
Self-exited Walking
- on flat floor -

[Ono et al.:2000]
Adaptive Oscillation
- Self-excited or Enforced -


• self-excited oscillation
• enforced oscillation + synchronization

oscillation by CPG (Central Pattern Generator)

- Mechanical system (pendulum / spring-mass)
  - reflex
  - self-excited oscillation
  - environment

- Mechanical system (pendulum / spring-mass)
  - entrainment
  - oscillator
  - forced oscillation
  - environment
Do we need CPG?

for generation of legged locomotion

neural system model
(CPG + reflexes)

central
oscillator

peripheral
non-oscillator

Grillner,
Cohen,
Ayers,
Ijspeert,
Taga,
Kimura, Tsuchiya,
...........

passive dynamics
(mechanism)

• passive dynamic walk
• spring-damper

Cruse,
Quinn,
............

Blickhan,
Full,
Koditschek,
Buehler,
Cutkosky,
............
CPG Models

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

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

essential for dynamic walking by Kimura (IJRR2003)
Which Sensor Information is used for Mutual Entrainment of CPG?

• Contact to the ground & AEP-PEP
  – Pearson (cat)
  – Cruse (stick insect)
  – Tsuchiya, Tsujita & Aoi (quadruped and biped)

• Joint angle
  – Grillner (lamprey)
  – Taga (biped)
  – Fukuoka & Kimura (quadruped)
  – ...........
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Legged Locomotion on Irregular Terrain

Conventional Method
- precise model
- trajectory planning
- control

Variety of irregularity

Problem
Autonomous Adaptation
Why Biological Concepts?

- Animals show marvelous ability of autonomous dynamic adaptation.

- In spite of difference in sensors and actuators, there exist same principles as a physical phenomenon between animals and robots.
## Control Methods According to the Speed

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

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<td><strong>upper neural system (learning)</strong></td>
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- 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** by ankle joint torque, control the angular velocity of the supporting leg

- Torque: Large
- Efficiency: low
- Needs large foot

**Touchdown Angle Control** by touchdown angle, control the forward speed of the next stance phase

- Torque: Small
- Efficiency: high
- Stabilization using the gravity

exchange of phases (switching)

touchdown angle
Stabilization of Forward Speed
- Touchdown Angle Control -

*Biper3 [1981]*
Miura & Shimoyama
 *[IJRR:1984]*

like walking on stilts
Stabilization of Forward Speed
- Touchdown Angle Control -

in biological system stepping reflex


Raibert:1984 the neutral-point foot-placement algorithm
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

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

[SCOUT-II]  [RHex]  [Sprawlita]
Hexapod Robots

RHex (2000-)

Sprawlita, … (2000-)

Self stabilization to stabilize the forward speed without measuring it
Quadruped Robot: ‘Tekken1’

20cm

- Weight: 3Kg
- 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

Sensor based adaptive walking on irregular terrain

[2001-2003]
Over Obstacles and Slopes
Characteristics of Legged Robots based on 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.

• Motion generation and adaptation by single system
Autonomous Adaptive Walking

For desirable adaptation, we must construct neural system carefully. Dynamic walking on irregular terrain requires physics, physiology, biomechanics, ...

by Taga [1991]

Coupled Dynamic based Motion Generation

Emergently Adaptive Dynamic Walking

Neural System Dynamics

Mechanical System Dynamics

Environment

coupling

interaction
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History of Emergently Adaptive Walking Study

Keywords: Emergence, Embodiment, Entrainment, Synergy

Self-organization and Emergence of Pattern in non-equilibrium open system

Prigogine, Haken [1970’-]

Shimizu, Yano, Taga [1980’-]

Kimura [1994--]

Robotics

sensory feedback to CPG

Bernstein [1940’]

Shik & Orlovsky [1960’]

Grillner, Mori [1970’-]

Cohen

Pearson, ....
What is Emergence of Pattern?

• “Global pattern (motion)” is generated in the interaction between non-linear dynamic system and environment, even though only “relations between elements” of the system are defined.

• The non-linear system can always generate the pattern for the change of environment according to its own dynamics.

Autonomous adaptation
Emergence of Pattern (1)

non-equilibrium open system

As the result of balance between input energy and consumed energy, structure (pattern) appears.

heat conduction

heat transmission
when thermal difference becomes large.

generation of pattern according to boundary condition
Emergence of Pattern (2)

generation of dynamic pattern (spiral wave) in non-equilibrium open system

Rayleigh & Bernard convection in thermohydrodynamic

BZ Chemical Reaction

deformable body of slime mold (fungi)

Common Principles: theory of non-equilibrium open system

Prigogine et al. “dissipation structure”
Emergence of Pattern (3)

- Generation of Skin Pattern -

Turing’s model of reaction-diffusion

[S.Kondo: Nature95]
Emergence of Pattern (4)
- Passive Dynamic Walking -

Potential energy
Energy loss by collision

Pattern is generated!
  • Bifurcation
  • Chaotic behavior

(Cornel Univ: 2000)
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Cohen

Pearson, ....
Bernstein Problems in Motor Control

[1940’-]

• Motor redundancy problem
  – synergy

• Context dependency problem
  – selection of appropriate motor pattern
Decerebrate Cat

Motivated by Bernstein Problems

The center of generation and adaptation of locomotion is located at the spinal cord.
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<td>upper neural system</td>
<td>lower neural system</td>
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<tr>
<td></td>
<td>(learning)</td>
<td>(CPG + reflexes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>visco-elasticity of muscles</td>
</tr>
<tr>
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<td></td>
<td>(self stabilization)</td>
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Locomotion Control Using Neural System Model

[by Ekeberg] [Northeastern Univ.]

BISAM

[by Taga] [Kyoto Univ.]

[by Ijspeert] [Iguana co.]

Patrush [UEC]
What is Neural System Model Control?

- Rhythm
- Phase Difference between Legs
- Tuning of Muscle Tone

Physiological Experiments Using Cats:
- S. Mori [1973]

Computer Simulation & Robot Experiments
- Kimura [1994-]

CPGs

Reflexes
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
CPG (Central Pattern Generator)

Neural Oscillator by Matsuoka[87] & Taga[91]

\[ \sum w_{ij} y_{ej} u_0 \]

\[ y_{ei} = \max(u_{ei}, 0) \]

\[ y_{fi} = \max(u_{fi}, 0) \]

Feed \( ei \) to \( ei \)

\[ u_0 \]

Extensor Neuron

Flexor Neuron

-1 < \( W_{hf} \) < -0.1

Pace

Trot

phase (stance/swing)

Excitatory Connection

Inhibitory Connection

extensor neuron of other N.O.'s

flexor neuron of other N.O.'s

Feed \( ei \)

Feed \( fi \)
Neural Oscillator

Matsuoka[87], Taga[91]

time constant

\[
\tau \dot{u}_{\{e,f\}i} = -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} + u_{0i} + \text{Feed}_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_{j}
\]

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

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

\[u_{\{e,f\}i} : \text{inner state of the neuron} \quad y_{\{e,f\}i} : \text{output of the neuron} \]

\[v_{\{e,f\}i} : \text{variable representing the self inhibition} \]

joint angle, body roll angle, etc.
Tuning of Muscle Tone

Joint PD Control as a Tonic Stretch Reflex

\[ trq_{jnt} = -K1_{jnt} (\theta^*_jnt - \theta_{jnt}) - K2 \dot{\theta}_{jnt} \]

\[ \theta^*_jnt = \begin{cases} \theta_{jnt}^{\text{stance}} \\ \theta_{jnt}^{\text{swing}} \end{cases} \]

\[ K1_{jnt} = \begin{cases} K1_{jnt}^{\text{stance}} \\ K1_{jnt}^{\text{swing}} \end{cases} \]
Phases are switched by CPGs

A

swing phase

y_i > 0

phase output of CPG

B

stance phase

y_i \leq 0

stiffness of joints

C

small

large
Mutual Entrainment

phase (stance / swing)

CPG \rightarrow Leg

oscillate with same cyclic period & fixed phase difference

hip joint ankle
important concepts #2

Change of Stiffness in Stance/Swing Phases

Tekken[2001-]

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]
Interaction between CPG and sensory feedback

reflexes, responses: CPGs’ phase dependent

- Tuning of Muscle Tone (Joint PD Controller)
  - pure reflex
    - torque output
    - sensory feedback $\rightarrow$ reflex delayed

- Rhythm Generation (CPG: Central Pattern Generator)
  - tunable reflex
    - phase (stance/swing) output
    - sensory feedback $\rightarrow$ response quickly

CPGs’ phase modulation
## Reflexes and Responses

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<th>Reflex Type</th>
<th>Sensed Value or Event</th>
<th>Activated On</th>
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<tr>
<td>Flexor reflex</td>
<td>Collision with obstacle</td>
<td>Sw</td>
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<tr>
<td>Stepping reflex</td>
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<td>Loss of ground contact</td>
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**Sp:** Supporting leg  
**Sw:** Swinging leg
Vestibular Reflex for Rolling

roll plane

upward-inclined leg

downward-inclined leg

Principles of Neuro Science, 3rd edn.
Vestibular Response for Rolling

\[
\text{Feed}_{e \cdot \text{roll}} = \delta(\text{leg}) \times k_{t \text{lrr}} \times (\text{body roll angle})
\]

\[
\text{Feed}_{f \cdot \text{roll}} = -\text{Feed}_{e \cdot \text{roll}}
\]

\[
\delta(\text{leg}) = \begin{cases} 
1, & \text{if leg is a right leg} \\
-1, & \text{if leg is a left leg} 
\end{cases}
\]
Vestibular Response for Rolling

\[ \text{Feed}_{\text{e.roll}} = \delta(\text{leg}) \times k_{\text{roll}} \times \text{(body roll angle)} \]

\[ \text{Feed}_{\text{f.roll}} = - \text{Feed}_{\text{e.roll}} \quad < 0 \]

<table>
<thead>
<tr>
<th>Right fore leg</th>
<th>E --</th>
<th>Right hind leg</th>
<th>E --</th>
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<tbody>
<tr>
<td>F +</td>
<td></td>
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Roll Motion Feedback to CPG

Without

With

\( T = 0.3 \text{ sec.} \)

17 cm

1.3 cm

17 cm
Rolling Motion as Standard of Rhythm

Rolling motion feedback to CPG

Stabilizing a gait

Adjusting phases of CPGs
## Reflexes and Responses

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*Sp*: supporting leg

*Sw*: swinging leg
Re-stepping Response
- in case of loss of ground support -

yi < 0

• The phase of a CPG moved to the stance phase.
• The contact of the leg is not detected within the fixed time.

Phase modification

• Extend the swing phase of the CPG

• The leg lands on the forwarder position.

Adjustment of initial condition of a stance phase

[Pearson et al: 1994]
Re-stepping Response Walking
- down a step 7cm in height -

without

with
Re-stepping Response Walking
- down a step 7cm in height -

- CPG output phase of the right fore leg
- Contact sensor output of the right fore leg

Swing and stance phases with re-stepping response highlighted.
Time [s]: 5.5 to 7.5

Swing and stance markers.
Motion Generation & Adaptation

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.
Adaptive Walking
Using a Neural System Model

Over an obstacle of 20% relative height to a leg

Over pebbles

The values of all parameters are fixed for unknown terrain of medium degree of irregularity.
Tekken2
- self-contained (power autonomous) -

on scattered grasses and pebbles  0.5 m/s
Bernstein Problems in Tekken

• Motor redundancy problem
  – Virtual spring-damper system (PD controller)

• Context dependency problem
  – CPG phase switches PD controller.
  – CPG phase switches reflexes.
  – CPG phase results in gait patterns.
  – CPG is the center of motion integration at the low level.
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Walking and Running of a Single Robot

no spring  ➔  huge energy loss

Tekken-1
Running in a bound gait [2002]
approx. 1 m/s

QRIO by Sony
Jogging [2004]
Mechanically Variable Stiffness of Joints - in order to increase adaptability and efficiency -

- Switch between a stance phase and a swing phase
- Switch between running and walking

Not yet
Quadruped Running Robot “Rush” under construction

- 4 DC motors at hip joints
- passive knee joint with spring
- design to suppress the collision impact to upper links and a body
Adaptive Running in a Bound Gait

• Generation of running in a bound gait from standing
  – Energy input
  – Gait generation

• Adaptive running on irregular terrain

Do we need the rhythm generator for running?

No! for steady running (spring-mass system)  Yes? for transitional running the rhythm generator may help
Ideas

- Use rhythm generator and torque generator

- Consider fixed points of quasi-passive running
  Koditschek et al., Buehler et al, Cham et al.,
  Hyon et al., Zhang et al., ………………… (2000-2004)

- Use DFC (delayed feedback control) to make
  motion converge to a fixed point
  Osuka et al., Hyon et al., ….. (2002-2004)
Delayed Feedback Control

Discrete Dynamical System

\[ x[n + 1] = \mathcal{F}(x[n], u[n]) \]

Energy of the system

\[ y[n] = \mathcal{G}(x[n]) \]

DFC (Delayed Feedback Control)

\[ u[n] = \mathcal{K}(y[n] - y[n - 1]) \]

gain
Ideas

• Use rhythm generator and torque generator

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• Use DFC (delayed feedback control) to make
  motion converge to a fixed point
  Osuka et al., Hyon et al., ….. (2002-2004)

• Use not energy but stance phase period
  as sensor information
  Cham et al., (2002)
Generator & Controller

Rhythm Generator
- Generate gait
- Adjust phase

Torque Generator
- Remain touchdown angle
- Provide energy input

stance phase period
Rhythm Generator

\[ \phi_l = \sin(\omega_l[n]t + \psi_l) + \phi_{0l}, \quad \omega_l[n] = \frac{2\pi}{T_i[n]} \]

- **Initial phase**
- **Angular frequency**
- **Phase of each leg**
- **Offset** (duty factor)
- **Cyclic period** calculated by DFC

**PD Control**
- \( \phi_l > 0 \)
- \( \phi_l \leq 0 \)

**Constant Torque Output**
- Swing phase of the rhythm generator
- Stance
Torque Generator

Depending on the leg phase generated by the rhythm generator, different control actions are assigned.

- $\phi_l > 0$  
  Swing phase: PD control
  \[
  \tau_l(t) = -K_p(\gamma_l - \gamma_l^{td}) - K_d\dot{\gamma}_l
  \]
  desired touchdown angle

- $\phi_l \leq 0$  
  Stance phase: constant torque
  \[
  \tau_l(t) = \tau_l^{st}[n]
  \]
  calculated by DFC
Proposed Delayed Feedback Control

Cyclic Period DFC

\[ T_l[n+1] = T_l[n] - K_{DF,T}(t_{lf}^{st}[n] - t_{lh}^{st}[n]) \]

Torque DFC

\[ \tau_l^{st}[n+1] = \tau_l^{st}[n] - \delta(l) K_{DF,\tau}(t_{lf}^{st}[n] - t_{lh}^{st}[n]) \]

\[ \delta(l) = \begin{cases} 
-1, & l = f: foreleg \\
1, & l = h: hindleg 
\end{cases} \]
Result:

The apex height and forward speed in the steady state are similar to the state of the fixed point of quasi-passive running.
Generating the Bounding Gait

The cyclic period of a rhythm generator accords with the cyclic period of motion of the leg and is mutually entrained!
Anti-disturbance Capability
-Running Up a Small Step with DFC-

**Adjustment based on DFC**
- forward speed
- jump height
- energy relative to the touchdown plane

\[ \times 3 \text{ slow} \]
Anti-disturbance Capability
-Running Up a Small Step with DFC-

Torque of hip joints of hind legs up

Converge at the steady state at the 17th step
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Legged Locomotion Control
by CPG & Torque Generator

- The rhythm generator works well in walking and (may be) running
  - synchronized with the physical oscillations
  \[ \text{mutual entrainment} \]

- CPG works well while combined with torque generator
  - change of stiffness (in walking)
  - DFC of hip joint torque (in running)

\[ \text{easily designed and understandable} \]
Mechanical Design

• CPG works well while combined with
  – torque generator &
  – well-designed mechanical system

  ◆ low friction at joints
  ◆ compliant joints
  ◆ small mass and inertia of legs
  ◆ .................
My Interest in Biology

• How sensor outputs are used for control
  – reflexes (torque adjustment at PD-controller)
  – response (CPG phase modulation)
  – ……

• Adaptive Mechanics
  – change of stiffness at joints
  – flexible body
  – passive or active ankle joint
  – ……..
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BigDog Project by Raibert

Boston Dynamics co. supported by DARPA

Target

- running speed: 10m/s
- climbing Mt. Fuji
Ministry of Economy, Trade and Industry (METI)

- Prototype Robot Exhib. by NEDO
  - 1,500,000,000yen (US$14,000,000)
  - 65 demos (university, institute, company)
  - *service robots in 2020*

  ◆ Reliability
  ◆ Usability
  ◆ Appearance
  ◆ Useful Functions?
  ◆ Costs
Tekken3

- active ankle joint
- 60W DC motor
- 9Kg only for mechanical parts

Tekken1 : 3Kg
Tekken2 : 4Kg
23W DC motor
Tekken4

- Same joints configuration with Tekken3
- Decoration of the exterior (asked by NEDO)
  - 1.5Kg
  - CFRP (Carbon Fiber Re-enforced Plastic)
  - US$18,000
- Vision Sensor
- Total: 10Kg
Jun.9-19, 2005
Navigation Using Laser Range Sensor

Laser Range Sensor

distance to the wall

tekken4

clear the walking direction

Tekken4 & Dr. Fukuoka
Ministry of Education and Science

“Mobiligence” Research Group in Japan

- Biology
  - Physiology
    - Takakusaki
  - Neuroethology
    - Kanzaki
    - Aonuma
  - Computational Neurosci.
    - Yano

- System Science
  - Tsuchiya
  - Ito

- Robotics
  - Legged locomotion
  - Multi robots
    - emergence of pattern

grant from JSPS
(like NFS)
3rd AMAM
Int. Conf. on Adaptive Motion in Animals and Machines
Sep.25-30, 2005 in Ilmenau, Germany

Biology,
Physiology,
Biomechanics,
Robotics,

........

http://wcms1.rz.tu-ilmenau.de/fakmb/index.php
Legged Locomotion Study is Nice!

**Biology**
- physiology
- neuroethology
- biomechanics
- ........

**Theory of non-equilibrium open system**
- emergence of pattern
- design of adaptive system
- ........

**Commercial Products**
- entertainment
- house caring dog robot?
- making money?
END