Biological Inspired Legged Locomotion
Control of a Robot

Hiroshi Kimura
Univ. of Electro-Communications
Tokyo, Japan

Katsuyoshi Tsujita
Kyoto Univ.
Japan

Outline

• Why we can/should learn from animals
• Common principles in robots and animals
• Applying biological concepts to a quadruped robot
• Energy consumption
• Discussions
• Future Works

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

Control of a arm

To keep the stable oscillation, Switching supporting/swinging phases non-linearity

the upper bound of the cyclic period of walking

A walking machine can walk down the slope without actuation.

Is the control necessary?

variety of irregularity

Problem Autonomous Adaptation
How we can learn from animals

Functions of Animals

Robots

mimicking

Functions of Animals

Principles

analysis

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

special link mechanism

wheel-leg

pantograph, parallel, ….

Hypothesis on Legged Locomotion
- principles of mechanism and motion -

low speed motion

Robots

Animals

A lot of alternatives in mechanism, devices and control methods

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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  – Mechanical design
  – Control method
  – Good examples
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Not Good Mechanical Design

Energy consumption : Large

Adaptability to irregular terrain : Small
“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
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

<table>
<thead>
<tr>
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<th>ZMP-based</th>
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<td>low / medium speed walking</td>
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<td>upper neural system (learning)</td>
<td>lower neural system (CPG + reflexes)</td>
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<td>role of sensor feedback</td>
<td>large</td>
<td>small</td>
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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

Angular Velocity Control
around contact point
by ankle joint torque,
control the angular velocity
of the supporting leg

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

Stabilization of Forward Speed
independent of the number of legs

Torque: Large
Efficiency: low
Needs large foot

Torque: Small
Efficiency: high

Stabilization using the gravity

Touchdown Angle Control -

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

like walking on stilts

Touchdown (Attacking) Angle
in Running

[Hackert, Witte & Fischer : AMAM2000]
[Buehler, et al. : AMAM2003]

Half Bound 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

Running on irregular terrain

Quadruped & Hexapod Robots

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

Hexapod Robots

RHex (2000-)
Sprawlita, … (2000-)

Self stabilization
to stabilize the forward speed without measuring it

Quadruped Robot: ‘Tekken’

- 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

Over an Obstacle of 20% Relative Height to a Leg

Over an obstacle 4.0cm in height
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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  - Rolling motion feedback to CPGs
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Physiology

- CPG (Central Pattern Generator)
  - Entrainment among neurons of CPGs
  - Entrainment with musculoskeleton
- Reflexes
  - Negative feedback
  - Positive feedback
- Higher Level

By Grillner, Cohen, Pearson, Prochazka, Mori, Drew, et al.
What is Neural System Model Control?

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

CPGs

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

Computer Simulation & Robot Experiments
- Kimura [1994-]

Tuning of Muscle Tone
Joint PD Control as a Tonic Stretch Reflex

\[
trq_{\text{joint}} = -K_1 \left( \theta^*_{\text{joint}} - \theta_{\text{joint}} \right) - K_2 \dot{\theta}_{\text{joint}}
\]

\[
\theta_{\text{joint}} = \begin{cases} 
\theta_{\text{stance}} \\
\theta_{\text{swing}} 
\end{cases}
\]

\[
K_1 = \begin{cases} 
K_{1, \text{stance}} \\
K_{1, \text{swing}} 
\end{cases}
\]

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]

Neural Oscillator

Matsuoka[87], Taga[91]

\[
\tau \dot{u}_{i} = -u_{i} + w_{e,i}v_{e,i} + w_{f,i}v_{f,i} + u_{0,i} + \sum_{j} w_{ij}y_{j}
\]

\[
v_{i} = \max(0, u_{i})
\]

\[
\dot{y}_{i} = -v_{i} + y_{i}
\]

Gaits

Trot: \( v = 0.6 \text{m/s}, T = 0.35s \)
Walk: \( v = 0.3 \text{m/s}, T = 0.6s \)

-0.7 \( W_{\text{hT}} \) -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

- 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

Passive ankle joint & Flexor reflex

- Over an obstacle 2.0 cm in height

Motion Adaptation & Sensory Feedback

- 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

- The legs should be free to move forward during the first period of the swing phase.
- The legs should land reliably on the ground during the second period of the swing phase.
- The phase difference between rolling motion of the body and pitching motion of legs should be maintained.
- The average of the forward speed be kept constant.
- The phase difference between legs be kept appropriately.

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- Waking in a long cyclic period is difficult to stabilize.

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

- Trot $T = 0.35s$, easy
- Walk $T = 0.6s$, difficult

- Tonic Labyrinthine Reflex for Rolling
- Vestibulospinal reflex/response for pitching

- Rolling motion feedback to CPG

Roll Motion Feedback to CPG

$Feed_{roll} = \delta(\text{leg}) \times k \times (\text{body roll angle})$

$Feed_{e.roll} = \text{Feed}_{roll} < 0$

- Without
- With $T = 0.3$ sec.
Rolling Motion as Standard of Rhythm

Rolling motion feedback to CPG

Stabilizing a gait

Adjusting phases of CPGs

Roll Motion Feedback to CPG

Slope of 5 & 3 degree inclination

Walking over Pebbles

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

Tekken-2

Energy Consumption

\[ \Box = \frac{P}{mgv} \]

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Discussion #1

What is Neural System Model Control?

ZMP Based

Limit Cycle Based

Equivalent?

CPG (Central Pattern Generator)

Interaction

Feedforward compensation of gravity and inertia force

Feedback correction of errors using sensor information

Discussion #1

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.
Autonomous Adaptive Walking
by Taga[1991]

Coupled Dynamic based Motion Generation

For desirable adaptation, we must construct neural system carefully.

Discussion #2

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

- Relation between the leg length or the stiffness and the time constant of CPG!
  - Choose the original cyclic period of CPG as
    \[ T_{eq} = \sqrt{\frac{\text{length of a leg}}{\text{mass} / \text{stiffness}}} \]

- Reflexes / Responses?

Discussion #3

CPG Models
Cruse, Elleberg
• 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

Argument (BC:2002)

essential for dynamic walking by Kimura (IJR2003)

Coupled Dynamics based Motion Generation

Future Works

Self-contained System & Outdoor Experiments

Visual Adaptation

Behavior

Gait Transition

Bipedal Locomotion

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Behavior and Tuning of Muscle Tone

[In Telluride, 2001]
[Of Kimura]

[S. Mori:1996]
[Prochazka:1988]

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continued …
END