Multi-Locomotion Robot

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Versatility of Locomotion Types

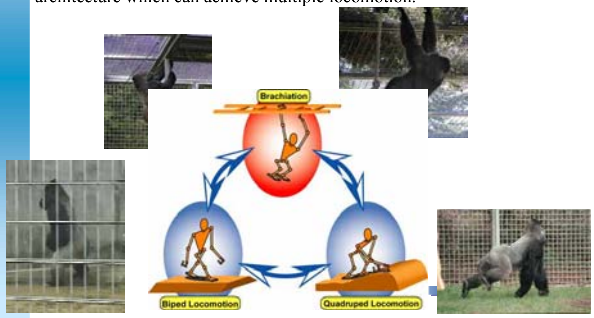
Crawling, walking, running, hopping, jumping, frying, swimming……..

Bio-Mimetic Robots

- Conventional work in Dexterous Motion Control
  - Hopping（M.H. Raibert1986）
  - Bipedal Walk（Takanishi1985, Kajita1986, Shimoyama1982）
  - Quadrupedal Walk（Hirose1986, Kimura2001）
  - Snake Locomotion（Hirose1990, J.W. Burdick 1993）
  - Brachiation (Fukuda1986, Saito1991, Nakanishi1999, Yamafuji1990)
  - Gymnastic Motion（Takashima 1991）
  - Standing Up（Doya, Morimoto 2001）
  - Acrobot(M.W.Spong1994, Mita2001）

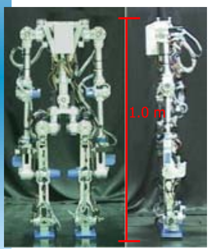
Selection of Locomotion Types

- In many cases, one creature has multiple types of locomotion in order to improve its mobility.
- The motivation of our study is to develop a robot mechanism and a control architecture which can achieve multiple locomotion.

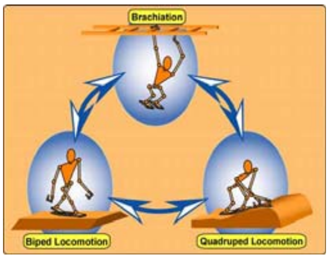


Gorilla Robot III

- Height : 1.0[m], Weight : 24.0[kg]
- 24DoF (Leg:6X2, Arm:5X2, Lumbar:2)
- Multi-locomotive robot (Biped, Quadruped, Brachiation)



Front View Side View



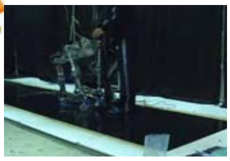
Concept of Multi-locomotion robot

Multi-Locomotion Robot

Brachiation

Bipedal Walk
Tomorrow's session
"Legged locomotion II".

Quadrupedal Walk

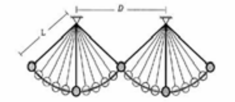


Brachiation

Brachiation

- Dynamics properties
  - Similar to a pendulum's one,
  - Dynamical motion utilizing gravity,
  - Low cost for locomotion due to useless of firm skeleton structure such as legs.

- Dynamics properties for motion control
  - Underactuated system (Rotation angle at ladder grasping point is not actuated.),
  - Variable constrain system (The grasping ladder sifts forward).



Conventional Brachiating Robots

- Pioneer work of brachiation robot (Brachiator I, 1985) Prof. Fukuda.
- Torque control on eigenfrequency (2-link robot, 1992) Prof. Yamafuji et all.
- Heuristic learning (Brachiator II, 1993) Dr. Saito et all.
- Hybrid Control (Acrobot, 1994) Dr. Spong
- 3-link robot (1996) Prof. Nishimura
- 3-dimensional motion (Brachiator III, 1996) Dr. Saito et all.
- Target Dynamics (Brachiator II, 1998) Dr. Nakanishi et all.

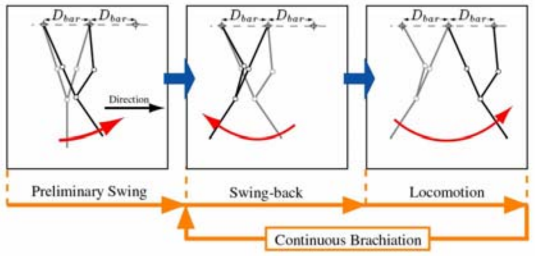
Brachiator I
(1985)

Brachiator II
(1993)

Brachiator III
(1996)

Focusing Point

- **Focusing point of our study is to realize a continuous brachiation using a redundant mechanism.**
- The continuous brachiation means that kinetic and potential energy at the end of a swing is used for the following swing.
- The continuous brachiation consists of iterative cycle of swing-back phase and locomotion phase after preliminary swing.



Continuous Brachiation

- Ladder interval: 0.4 m

Target Motions

- We propose energy-based swing control to enhance the continuous brachiation for various ladder intervals.

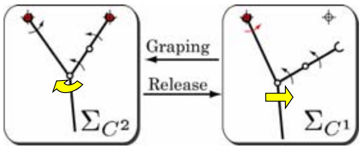
- Two experiment fields
  - Uniform Ladder Brachiation

    (The ladder interval is even, but it is changed each trial.)
  - Irregular Ladder Brachiation

    (The ladder interval varies in every swing.)

Energy Control Strategy

- The necessary energy for continuous locomotion should be charged in one swing.
  - The energy should be charged in swing-back phase, because two arms are constrained by each ladder, and the angular velocity of the body swing is directly controlled .
  - A system in locomotion phase is underactuated. A small mount of energy is obtained in one swing.



Swing-back Phase

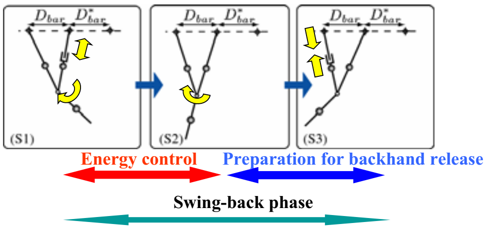
Energy Control

Locomotion Phase

(Constant Energy)

Energy Control Strategy

- The necessary energy is charged by controlling an angular velocity of the body swing.
- The total energy is evaluated at a moment S2 when two arms are stretched.
- After the moment "S2", the robot starts to release the backhand from the ladder so that total energy could not be charged.



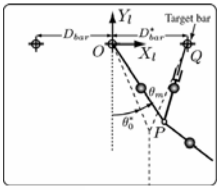
Energy control

Preparation for backhand release

Swing-back phase

Calculation of Target Total Energy

- We calculate the target total energy enough to catch target ladders with various intervals.



- Target total energy at grasping moment : E^*

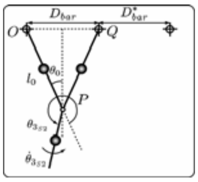
$$E^* = P_{L3}$$
$$P_{L3} = P^*_1 + P^*_2 + P^*_3$$
$$P^*_1 := -m_1 g \frac{l_0}{2} \cos(\theta^*_0 + \theta_m)$$
$$P^*_2 := P^*_1$$
$$P^*_3 := -m_3 g \left(l_0 \cos(\theta^*_0 + \theta_m) + \frac{l_3}{2} \cos(\theta^*_0 + \theta_m + \theta_{3_{L3}}) \right)$$
$$\theta^*_0 := \sin^{-1} \left(\frac{D^*_{bar}}{2l_0} \right)$$

- Supposed that
  - the current ladder interval D_{bar} , the next ladder interval D^*_{bar}
  - Amplitude allowance θ_m

Controller Design for Swing-back

- Total energy at the moment "S2"

$$E_{S2} = P_{S2} + K_{S2}$$
$$P_{S2} = P_1 + P_2 + P_3$$
$$P_1 = -m_1 g \frac{l_0}{2} \cos\theta_0$$
$$P_2 = P_1$$
$$P_3 = -m_3 g \left(l_0 \cos\theta_0 + \frac{l_3}{2} \cos(\theta_0 + \theta_{3_{S2}}) \right)$$
$$K_{S2} = \frac{1}{2} m_3 \left(\frac{l_3}{2} \dot{\theta}_{3_{S2}} \right)^2$$



[Swing Phase]

- Necessary kinetic energy at the moment "S2"

$$K^d_{S2} = E^d_{S2} - P^d_{S2} = E^* - P^d_{S2}$$

- The desired angular velocity of the body swing

$$\dot{\theta}^d_3 = -\frac{2}{l_3} \sqrt{\frac{2}{m_3} \left(E^* - P^d_{S2} \right)}$$

Controller Design for Swing-back

- The body angle at the moment S2, θ^d_3 is determined in order to minimize the energy loss.
  - The rotation center of a robot is shifted at the moment "S2" from point O to point Q.
  - The kinetic energy is dumped by this shift at this moment.
  - The velocity vector and the position vector should be orthogonal in order to minimize the energy loss.

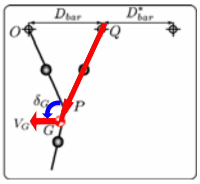
$$\boxed{\mathbf{QG} \cdot \mathbf{V_G} = \mathbf{0}} \quad \delta_G = 90[deg]$$

$\mathbf{V_G}$: Velocity vector of center of gravity of a robot

$\mathbf{QG}$: Position vector of center of gravity

δ_G : Angle of between two vectors above

[Swing Phase]



Controller Design for Swing-back

- The body swing is expressed by cosine function

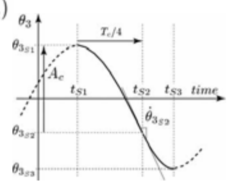
$$f_{q3} := \theta_3^d = A_c \cdot \cos\left(\frac{2\pi}{T_c}(t - t_{S1})\right) - \theta_{3_{S2}}$$

$$A_c = \theta_{3_{S1}} - \theta_{3_{S2}}$$

$$\dot{\theta}_{3_{S2}} = -A_c \cdot \frac{2\pi}{T_c}$$

- Period of swing-back motion

$$T_c = l_3(\theta_{3_{S1}} - \theta_{3_{S2}})\pi\sqrt{\frac{m_3}{2\left(E^* - P_{S2}^d\right)}}$$



Controller Design for Swing-back

- The length of forehand is expressed by cubic spline function.

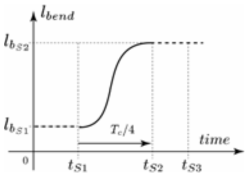
$$f_{lb} := l_{bend}^d = F_{spln}(t)$$

$$\dot{F}_{spln}(t_{S1}) = \dot{F}_{spln}(t_{S2}) = 0$$

$$F_{spln}(t_{S1}) = l_{2_{S1}}, F_{spln}(t_{S2}) = l_0$$

- The reference elbow angle of forehand is solved geometrically.

$$f_{q2} := \theta_2^d = \cos^{-1}\left(\frac{D_{bar} - l_0 \sin\theta_1}{l_{bend}^d}\right) - \theta_1 + \frac{\pi}{2}$$



Controller Design for Locomotion

- The reference trajectory of a free hand is designed using ellipse equation.

$$\left(\frac{x_q - x_0}{r_0}\right)^2 + \left(\frac{y_q}{d_c}\right)^2 = 1, x_0 := \frac{D_{bar}^* - D_{bar}}{2}, r_0 := \frac{D_{bar}^* + D_{bar}}{2}$$

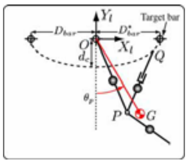
$$x_p = l_0 \sin\theta_1,\ y_p = -l_0 \cos\theta_1$$

$$x' = \frac{2r_0}{\theta_0^* + \theta_0}(\theta_1 + \theta_0) - r_0,\ y' = -d_c\sqrt{1 - \left(\frac{x'}{r_0}\right)}$$

$$x_q = x' + \frac{1}{2}(D_{bar}^* - D_{bar}),\ y_q = y'$$

$$f_{lb} := l_{bend}^d = \sqrt{(x_q - x_p)^2 + (y_q - y_p)^2}$$

$$f_{q2} := \theta_2^d = \cos^{-1}\left(\frac{x_q - x_p}{l_{bend}^d}\right) - \theta_1 + \frac{\pi}{2}$$

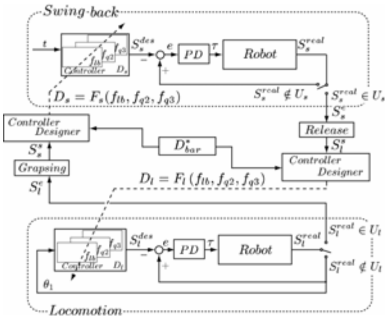


[Locomotion Phase]

- The reference trajectory of body swing is designed symmetrically so that total energy is kept constant.

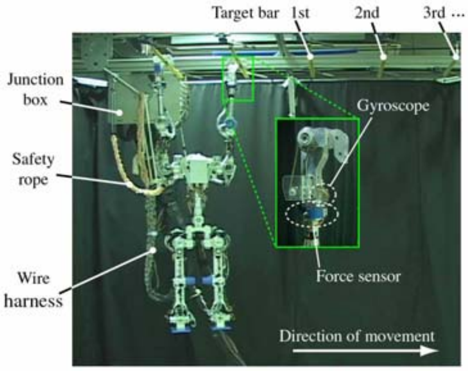
$$f_{q3} := \theta_3^d = \frac{\theta_{3s}}{\theta_{1s}}(\theta_1 - \theta_{1s}) + \theta_{3s}$$

Block Diagram for Continuous Locomotion



$$S = [X, \dot{X}, \ddot{X}]^T, X = [\theta_1, \theta_2, \theta_3, l_{bend}]^T$$

Experimental Settings



Uniform Ladder Brachiation

- Parameter settings
  - Constant Ladder Interval： $D_{bar}^* = D_{bar}$
    - different ladder interval from 0.30[m] to 0.45[m] with 0.05[m] step.

  1) $D_{bar} = 0.30$, 2) $D_{bar} = 0.35$, 3) $D_{bar} = 0.40$, 4) $D_{bar} = 0.45$

  - Amplitude allowance for grasping margin at grasping moment

$$\theta_m = 5.0[deg]$$

  - Desired amplitude angle at grasping moment

$$\theta_1^d = \theta_0^* + 5.0[deg]$$

  - Period of Swing-back motion for each ladder interval: T_c.

D_{bar}[m]	$T_c/4$[s]
0.30	0.455
0.35	0.451
0.40	0.449
0.45	0.447

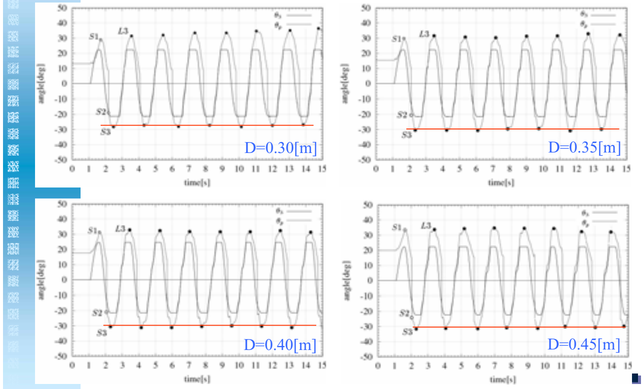
Uniform Ladder Brachiation

Continuous Brachiation

-Uniform Ladder-

Fukuda Lab., Nagoya Univ.

Uniform Ladder Brachiation



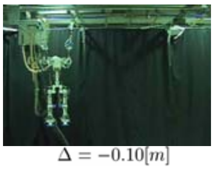
Irregular Ladder Brachiation #1

- Irregular Ladder Condition: $D_{bar}^{*} = D_{bar} + \Delta$
  - Attenuation: $\Delta < 0$
    - $\Delta = -0.05[m]$,
      $D_{bar} = 0.45 \rightarrow 0.45 \rightarrow 0.40 \rightarrow 0.35 \rightarrow 0.30 \rightarrow 0.30[m]$
    - $\Delta = -0.10[m]$,
      $D_{bar} = 0.45 \rightarrow 0.45 \rightarrow 0.35 \rightarrow 0.35[m]$
  - Excitation: $\Delta > 0$
    - $\Delta = 0.05[m]$,
      $D_{bar} = 0.30 \rightarrow 0.30 \rightarrow 0.35 \rightarrow 0.40 \rightarrow 0.45 \rightarrow 0.45[m]$
    - $\Delta = 0.10[m]$,
      $D_{bar} = 0.30 \rightarrow 0.30 \rightarrow 0.40 \rightarrow 0.40[m]$

	$\Delta = -0.10$	$\Delta = -0.05$	$\Delta = 0$	$\Delta = 0.05$	$\Delta = 0.10$
$Tc/4[s](D_{bar} = 0.45)$	0.520	0.470	0.447	–	–
$Tc/4[s](D_{bar} = 0.40)$	0.549	0.494	0.449	0.413	–
$Tc/4[s](D_{bar} = 0.35)$	–	0.521	0.451	0.434	0.400
$Tc/4[s](D_{bar} = 0.30)$	–	–	0.455	0.440	0.421

Irregular Ladder Brachiation #1

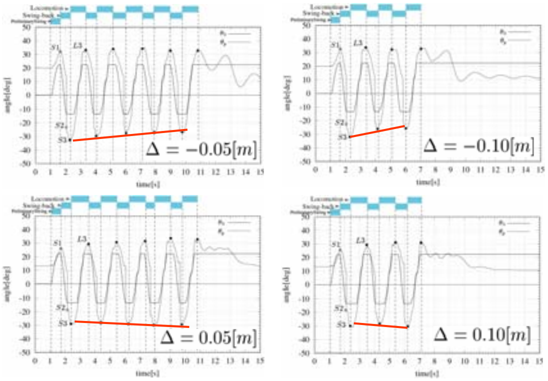

$\Delta = -0.05[m]$


$\Delta = -0.10[m]$

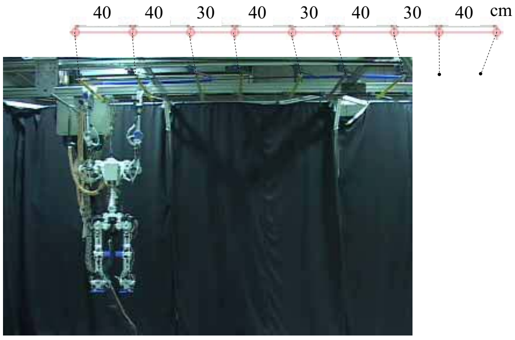

$\Delta = 0.05[m]$


$\Delta = 0.10[m]$

Irregular Ladder Brachiation #1

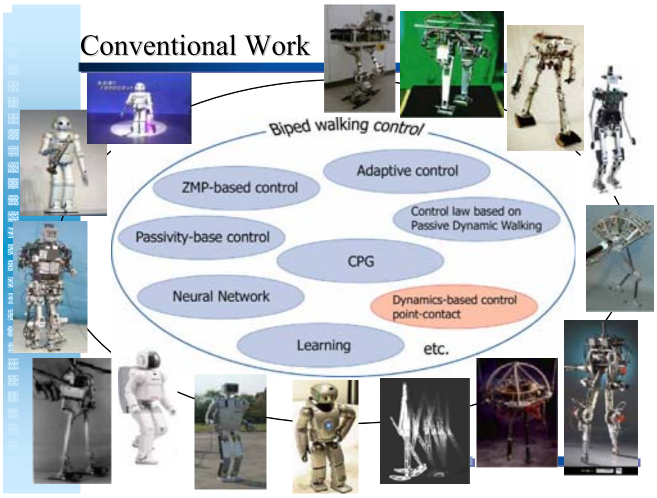


Irregular Ladder Brachiation #2

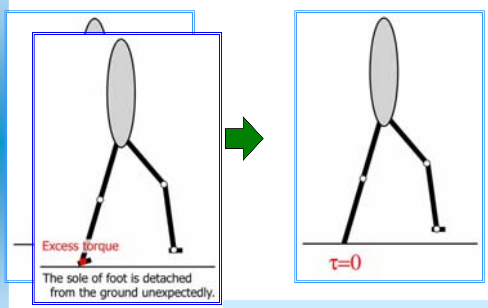


3D biped walking design

Conventional Work



Background



Point-contact makes it possible

- to take advantage of the robot dynamics
- to realize the natural walking
- to adjust to the ground irregularity

Point-Contact Method

Previous Researches

- "Dynamic walk of a robot"
  H. Miura & I. Shimoyama (Tran. RA, 1984)
- "Dynamic Walking Control of a Biped Robot Along a Potential Energy Conserving Orbit"
  S. Kajita, T. Yamaura & A. Kobayashi (Tran. RA, 1992)
- "Time-scaling control for an underactuated biped robot"
  C. Chevallereau (Tran. RA, 2003)
- "Experimental Validation of a Framework for the Design of Controllers that Induce Stable Walking in Planar Bipeds"
  E. R. Westervelt, G. Buche, and J. W. Grizzle (IJRR, 2003)
- "Passive Dynamic Autonomous Control of Biped Walking"
  M. Doi, Y. Hasegawa and T. Fukuda (Humanoids 2004)

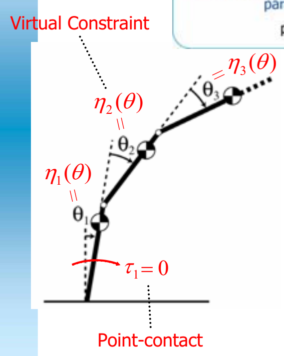
We proposed PDAC previously.

PDAC (Passive Dynamic Autonomous Control)

Virtual Constraint

"a set of holonomic constraints on the robot's actuated DoF parameterized by the robot's unactuated DoF"

proposed by E.R.Westervelt and J.Grizzle et al.



Robot dynamics

$$\frac{d}{dt}\left(\mathbf{M}(\boldsymbol{\Theta})\dot{\boldsymbol{\Theta}}\right)-\frac{1}{2}\frac{\partial}{\partial \boldsymbol{\Theta}}\left(\dot{\boldsymbol{\Theta}}^{T}\mathbf{M}(\boldsymbol{\Theta})\dot{\boldsymbol{\Theta}}\right)-\mathbf{G}(\boldsymbol{\Theta})=\boldsymbol{\tau}$$

Point-contact $\tau_1 = 0$

Virtual Constraint $\boldsymbol{\Theta} = \boldsymbol{\eta}(\theta)$

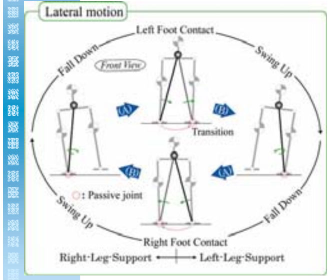
Phase around the contact point

$$\dot{\theta} = F(\theta)$$

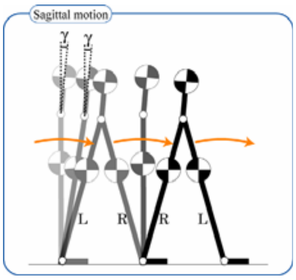
1-dimensional autonomous system

3D Biped Walking

For simplicity, 3-dimensional motion is divided into lateral and sagittal one.



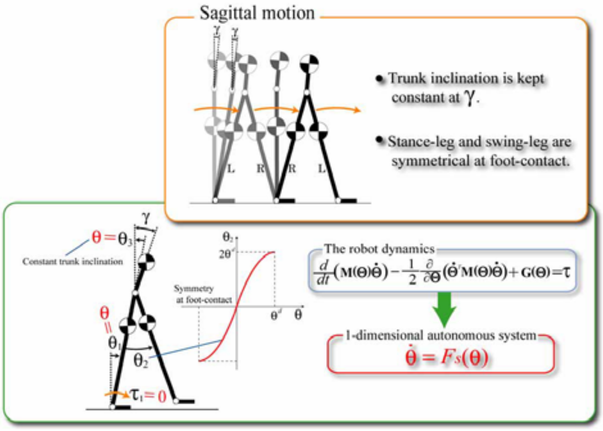
Inverted-pendulum model



3-link model

Assumption:
Lateral and sagittal dynamics are approximately independent each other.

Sagittal Motion



- Trunk inclination is kept constant at γ.
- Stance-leg and swing-leg are symmetrical at foot-contact.

The robot dynamics

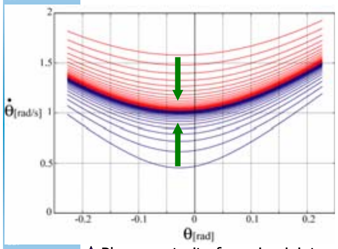
$$\frac{d}{dt}(\mathbf{M}(\Theta)\dot{\Theta})-\frac{1}{2}\frac{\partial}{\partial\Theta}(\dot{\Theta}^{T}\mathbf{M}(\Theta)\dot{\Theta})+\mathbf{G}(\Theta)=\tau$$

1-dimensional autonomous system

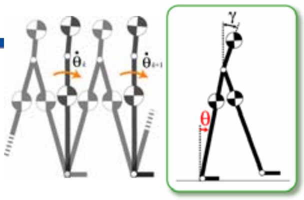
$$\dot{\theta}=F_S(\theta)$$

Sagittal Motion

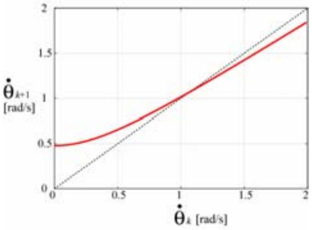
Constant step-length



▲ Phase portrait of passive joint

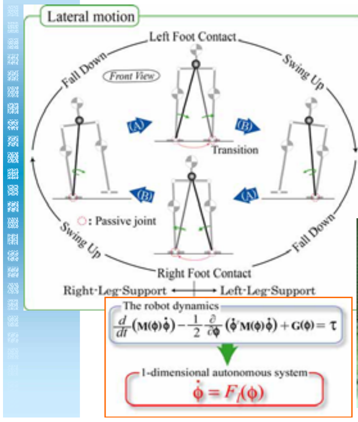


▼ Map of angular velocity



Trunk inclination γ =0.075[rad]
Step-length = 0.2[m]

Lateral Motion

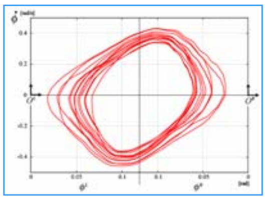


The robot dynamics

$$\frac{d}{dt}(\mathbf{M}(\phi)\dot{\phi})-\frac{1}{2}\frac{\partial}{\partial\phi}(\dot{\phi}^{T}\mathbf{M}(\phi)\dot{\phi})+\mathbf{G}(\phi)=\tau$$

1-dimensional autonomous system

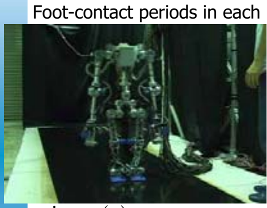
$$\dot{\phi}=F_l(\phi)$$



Synchronization

Foot-contact periods in each plane are necessary to be identical.

T_l



T_s

$\dot{\phi}=F_l(\phi)$ Lateral phase

$\dot{\theta}=F_s(\theta)$ Sagittal phase

$$T_l=\int\frac{1}{F_l(\phi)}d\phi \Rightarrow \text{Synchronization} \Leftarrow T_s=\int\frac{1}{F_s(\theta)}d\theta$$

Lateral period

Sagittal period

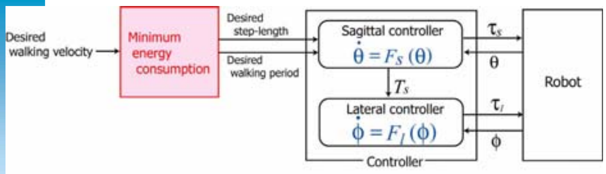
The amplitude of the lateral sway motion is decided
so that sagittal step-length is kept constant at desired value.

Upper layer controller

Upper Layer Controller

Step-length and walking period are necessary to
be decided according to the desired velocity.

There are innumerable combination
of step-length and walking period
that satisfies the desired walking velocity.



Upper Layer Controller

Assumption

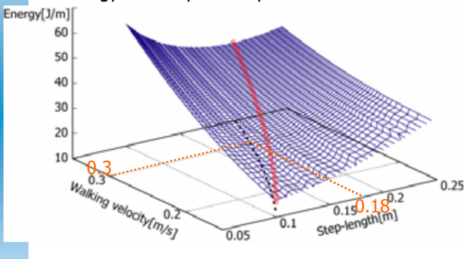
- All joints have no viscosity and no friction.
- The ground is flat and uniform.
- Foot-contact is perfectly inelastic collision.

As the energy consumption, energy/step-length[J/s] is used.

$$E = \frac{\int \boldsymbol{\tau}^T \dot{\boldsymbol{\Theta}}\, dt}{\lambda} = \frac{\int \boldsymbol{\tau}^T d\boldsymbol{\Theta}}{\lambda} \qquad \lambda : \text{step-length}$$

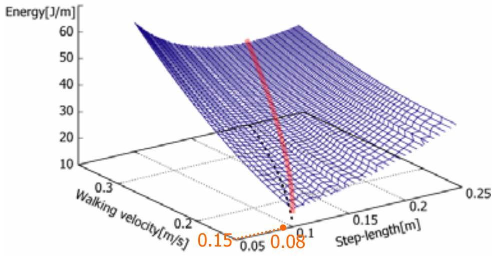
Upper Layer Controller

Energy consumption map



Experiment

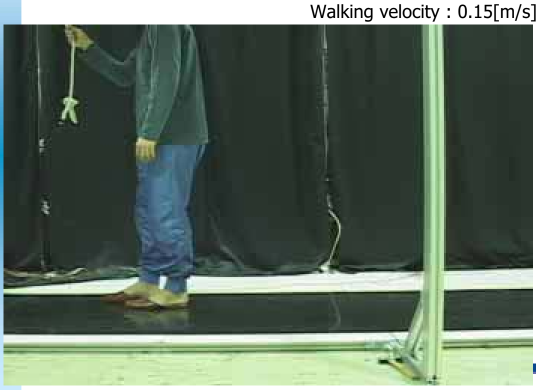
Experiment (Slow walking)



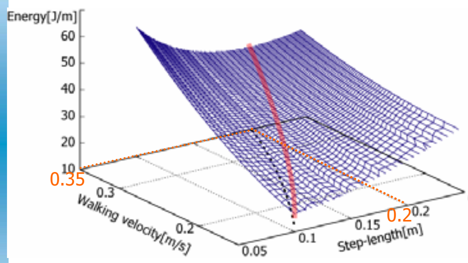
Step-length : 0.08[m]
Walking velocity : 0.15[m/s]

Experiment (Slow walking)

Step-length : 0.08[m]
Walking velocity : 0.15[m/s]



Experiment (Fast walking)

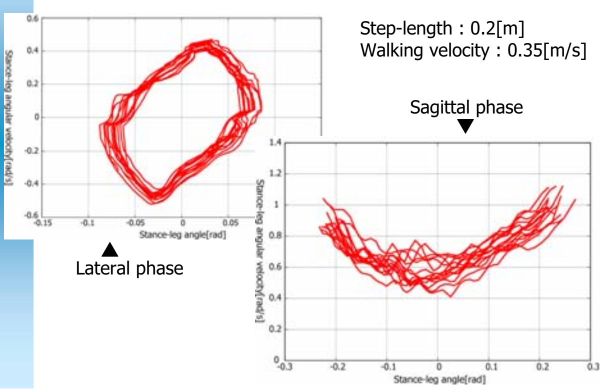


Step-length : 0.2[m]
Walking velocity : 0.35[m/s]

Experiment (Fast walking)

Step-length : 0.2[m]
Walking velocity : 0.35[m/s]

Experimental results



Step-length : 0.2[m]
Walking velocity : 0.35[m/s]

Sagittal phase

Lateral phase

Summary

- Proposal of multi-locomotion robot.
  - The robot could improve its mobility by selecting the proper type of locomotion according to its environment and purpose.
- Performance enhancement of brachiation.
  - Proposal of energy-based swing control.
  - Implementation of uniform ladder brachiation and irregular ladder brachiation.

- Lateral and sagittal motion designed by PDAC.
- Total motion designed for the minimum energy consumption
- 3D dynamic walking at various velocity