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On Recent Bio-mimetic Studies of Legged Locomotion

--- Diversity, Adaptability and Energy Consumption for Hexapod, Quadruped and Biped

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Abstract

This paper introduces the recent active legged locomotion researches performed in RIKEN BMC from the point of view of bio-mimetic system control. It is shown how biological discoveries, such as the primitive module vector fields interpolation of spinally dissected frogs, the adaptive locomotion pattern changes of decerebrate cats as well as the energetically efficiency of human walking, can be mathematically formulated and practically realized in legged robots range from hexapod, quadruped to biped.

1. Introduction

Legged locomotion is one of the most interesting motor functions for the biological system to move while interacting adaptively with its complex environment. Bio-mimetic study of locomotion is an important approach not only necessary to understand the elegant motor control mechanism of central nervous system but also useful for realizing the next generation of more flexible and intelligent environmental adaptive robotic systems.

During these several years, active researches have been performed within RIKEN BMC on the bio-mimetic studies of legged locomotion range from hexapod, quadruped to biped. The main objective is to clarify the *diversity*, *adaptability* as well as *efficiency* and *simplicity* of the basic control mechanism inherent in animals' locomotion control and its application in robotics.

In this paper, after describing three levels of bio-mimetic studies of motor behavior, we show that, the primitive module vector field interpolation, which was investigated in the spinally dissected frogs by Mussa-Ivaldi et al., can effectively be applied in the hierarchical control of a hexapod robot to realize diversity of locomotion with respect to environmental conditions. This control structure makes it easier for the robot to treat directly the logical symbolic information from sound recognition as well as visual cognition [1]-[4] in performing the corresponding dynamic locomotion. We extended the framework of autonomous decentralized system control to mathematically formulate the adaptive behavior of a decerebrate cat walking on a changing treadmill and its practical application by a quadruped robot [5]-[8]. In addition, we introduce our original motion capture system for measuring, analyzing and dynamic simulating of human motions with high precision. It is proposed that the biped robot can realize locomotion easier and energetically more efficient if we integrate both the characteristics of human locomotion as well as recent hot passive dynamic walking researches of a biped robot [9]-[11].

2. Bio-mimetic Study of Legged Motions

The ultimate goal of bio-mimetic study on biological motor behaviors is to discover and to realize the natural and beautiful animal motions with higher energy efficiency and environmental adaptability. This study can be performed from three different levels. The first level, which is the most simplest and also direct way, is to mimic the kinematical motion phenomenon such as to measure the human motion trajectory and to playback it by a robot after some coordination transformations. The main problem of this level is the robustness, especially the robustness to unpredicted disturbances. The second mimic level is to understand the mechanics and dynamics of the biological motions. Within this level of study, the recent passive dynamic walking as well as varying rotational joint axis, which is completely different from the mechanism of the present robot joint with fixed axis joint, may give us more hints towards discover the energetically efficient locomotion. The main difficulty here is that even the most advanced system control theory cannot cover this analysis and control design. The third level requires to model mathematically the function of central nervous system such as: nonlinear neural oscillator, central pattern generator (CPG), base fields interpolation as well as neural

networks. The modeling of soft and powerful muscles is also fascinating as seem from robotic actuators. However, the limitation of biological experiment still makes it unclear about what is really the principle and essence of central nervous system.
The mathematical difficulties of locomotion come from the system's nonlinearity, redundancy, nonholonomic constraints, impact state jumping et al.. The key physical characteristics we mainly focused on are the system's energy consumption, zero moment point (ZMP), angle momentum, equivalent mass center, stability and body balance, et al.. If we look at the motion of one leg, then the mathematic parameters of: Frequency of oscillation, the relative phase difference, the stride as well as the rate between stance phase and swing phase et al. characterize the basic gait pattern. In the following, we describe our researches of hexapod, quadruped and biped, respectively. S**ection 3** relates to the adjustment of stride, **Section 4** adjusts the relative leg phase, and Section 5 compares the human biped and passive dynamic walking from the point of view of energy changes.

3. Diversity of Hexapod Locomotion

Unlike the critical problems of body balance and stability of dynamic walking in biped locomotion, the central point in hexapod is rather to solve coordination for multi-legs with redundant D.O.F. to realize in real time the *diversity* of locomotion with respect to environmental changes.

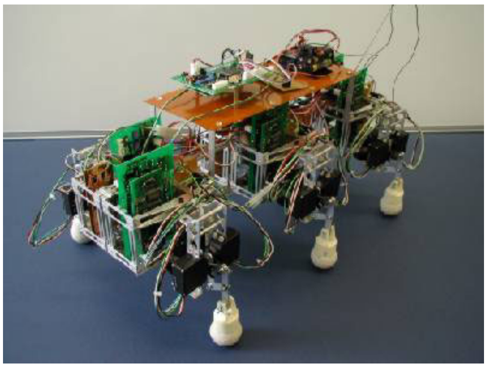


Fig.1. Modular hexapod robot with two layered hierarchical control system developed in BMC

3.1 Hexapod Robot System

Towards this objective, a modular hexapod robot has been constructed as seen in **Fig.1**. The control system of this robot is constructed from two layers, hierarchically.
The upper layer consists of sensors, a processor and communication channels. The processor here plans the total body movement of the robot based on its visual sensor information and the human sound commands from wireless communication channels. The motion plans are then translated and broadcasted to all the sub-controllers in the lower layer to determine the respective trajectory of each leg. For one kind of robot movement, the same set of commands is sent to all the lower layer controllers only one time, which reduced greatly the communication cost between the two layers.
On the other hand, the lower layer consists of six uniform sub-systems. They are arranged in two lines along the rostral-caudal line. Each sub-system has one leg with 3 D.O.F., one processor, three touch sensors and one toggle switch. When a sub-system is connected to another one, the touch sensor is turned on and the leg can detect its neighbor. Switching a toggle switch tells a subsystem on which side (left or right) it is arranged. This information allows the subsystems to recognize their location within the robot body as well as the direction of the robot's head. Each processor of the subsystem has three communication channels: two with the neighbors, and one with the upper layer controller. The former channels link each subsystem locally and send data bi-directionally. Through the interaction via these channels, all the lower layer controllers can decide their own swing timing, which guarantees a continuous stable gait pattern. The later channel transfers the command from the upper layer to the lower layer. Based on this information, each lower layer processor determines an adequate trajectory for its leg.
Not only the hardware but also the software of all subsystems is the same. This homogenous structure design has three advantages from the engineering point of view: First, since one controller controls only one leg, a system covered by one controller is quite small, which simplified the program code development. Second, the structure of each subsystem is also simple, which increased the robustness of the hardware. The last advantage is the ease of repairs, namely, by replacing only the defective subsystem with a new one, the whole robot system can be rapidly recovered from malfunction.

3.2 Biological Study of Vector Field

Inspired by neuroscience of CPG as well as autonomous decentralized system control theory, we designed local interactions between each oscillator to coordinate the legged motions. In order to realize in real time the diversity of locomotion with respect to environmental changes, we introduced the method of base vector field interpolation.

The base vector field interpolation phenomenon was biologically found and mathematically formulated by Mussa-Ivaldi et al. when they investigated the micro-electrical stimulation of the spinally dissected frogs. It was found that:

1) When stimulating a point on the spinal cord using microelectrodes, the isometric forces of the frog's leg tends to converge to a single equilibrium point.
2) The point is shifted if we stimulate another location on the spinal cord.
3) Most interestingly, when we stimulate the two locations on the cord simultaneously, the leg force vector field tends to be a linear combination of above two vector fields.

As the conclusion, it was proposed that the primitive motor functions are represented in the form of base vector fields, the complex motor behavior is generated by linear interpolation of these base vector fields.

3.3 Robotic Implementation

Inspired by this biological study, in our hexapod locomotion research, we implement it as follows.

1) We first define the robot's body frame attached along the body of the robot.
2) Three kinds of base vector fields defined on the robot's body frame that representing two translations and one rotation movement, respectively as shown in **Fig.2**, are saved in all subsystems of the lower layer.
3) The upper layer controller process the symbolic visual sensor information about its environment as well as the sound commands from human operator and transfer them into the weight parameters of three vector fields, the weights are sent to all subsystems.
4) The subsystems then calculate the weighted vector field and select the specific vectors according to their leg locations within the body.
5) The selected vector corresponded to the desired leg trajectory within the body frame for the feedback control of a leg motion, where the vector length is the stride and the vector direction is the direction of the leg's coxa.

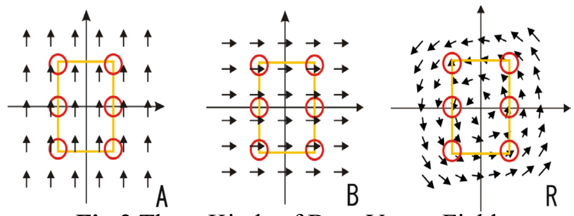
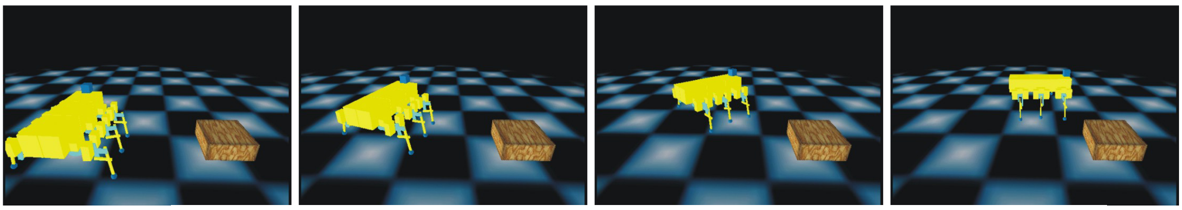
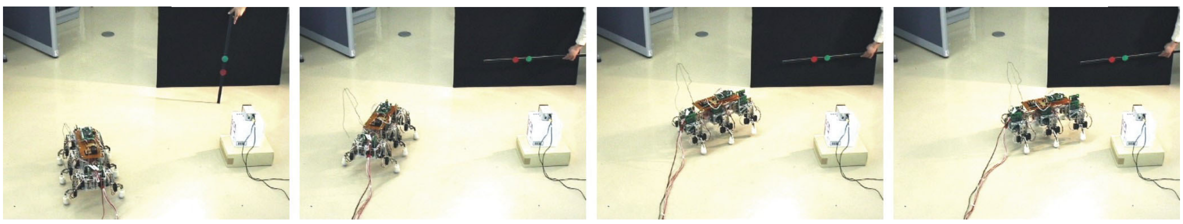


Fig.2 Three Kinds of Base Vector Fields



(a) 3D Dynamic Simulation Results of a Hexapod Robot's Diverse of Locomotion



(b) Vision-based Control Results of a Hexapod Robot's Diverse of Locomotion

Fig. 3 Experiment and Simulation Results of a Hexapod Robot

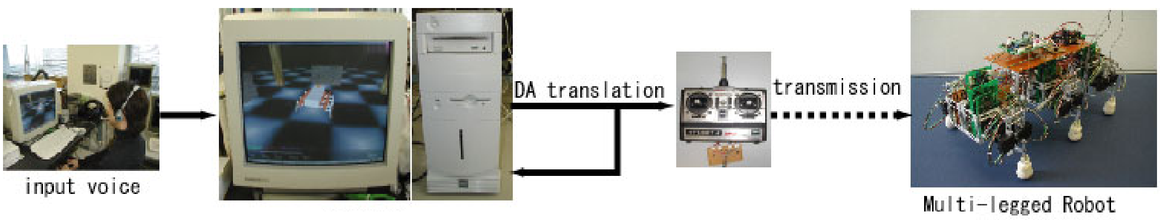


Fig. 4 Sound Communication between Human and a Hexapod Robot

Based on this vector field based control, it is succeeded for us to control the robot's diverse of dynamic locomotion simply and directly from the symbolic information of sound and visual, this information are transferred to the weight parameters of the base vector fields at the upper layer and are sent to the lower layer for the leg subsystem to interpolate and physically realized.
The examples of experiment and 3D dynamic simulation results of vision-based locomotion are shown in **Fig.3**, and the communication between human and the robot is shown in **Fig.4**.
The gait emergence algorithm of this hexapod robot based on energy consumption is given in [4].

4. Adaptive Locomotion of Quadruped

The above control mechanism adjusted the leg strides according to the vector field but not the relative leg phases. As seem from the relative phase between each leg, the hexapod robot only performed the simple static tripod gait. In most cases, relative leg phases determine the essence of gait pattern. In this section, we show how to adaptively adjust the relative phase so as to mimic the biological study result on the adaptive gait adjustment of a cat by Yanagihara et al..

4.1 Adaptive Gait of Decerebrate Cat

As shown in **Fig.5**, Yanagihara et al. designed a sophisticated experiment to study the control mechanism of cerebellum and the adaptive walking behavior of a decerebrate cat. In this experiment, a special treadmill with four independent belts is used. Firstly, four belts were driven with the same speed and the cat was set to walk on the treadmill. After this training, one belt was driven faster than the other three ones. This change becomes a perturbation to influences the relative phase between the legs. Initially, the cat fails to walk on this treadmill and no steady gait pattern can be recorded, however after many trails, new gait generated. More surprisingly, in the next trail after the cat generated the new gait pattern, it can walk with this pattern at the very beginning of the trail. However, when setting back the belt to the original same speed, the cat cannot walk with the original gait.

4.2 Adaptive Mechanism and Quadruped Robot

Based on these biological results, we formulated mathematically the adaptive mechanism and constructed a quadruped robot as shown in **Fig.6**.
This robot is driven by 8 AC motors of 30W with about 10 times of speed reduction by gears and timing belts. Each leg has 2 D.O.F., and load-cells are attached on the foot to measure the interaction force vector between the leg and the ground. The mechanical structure and the control algorithms of four legs are basically the same.

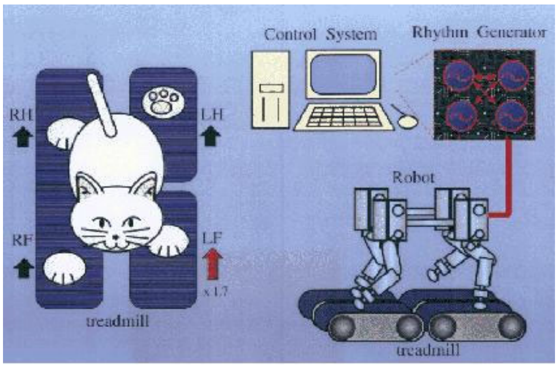


Fig.5 Experiments of a Decerebrate Cat

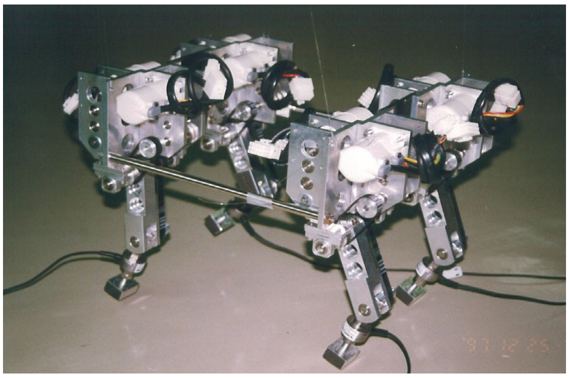


Fig.6 Quadruped Robot Developed in BMC RIKEN

Our adaptation algorithm extended the autonomous decentralized system theory which was proposed for controlling the order of the larger scale nonlinear system through designing the local interactions between each subsystem. Applying this theory, it first defines the interaction between each oscillator of a leg by designing a gradient system in the relative phase space. The minimum of the potential function of the gradient system was given previously. When there are disturbance on the leg, the real relative leg phase of the new gait will leave from the minimum potential point, however, if the disturbance disappeared, the potential function will force the relative phase back to the original minimum point again. This function cannot represent the biological fact that after training on new treadmill condition, the cat forgot its original gait.
In our algorithm, by using impedance control with force feedback of the leg as well as disturbance

estimation, the minimum point of the potential function is adjusted towards reducing the interaction between each leg. This adaptive adjustment algorithm is also realized by only by each sub-controller in a decentralized way without using any central controller. As a result, it is reported in [4] and [6] that, our simulation results of adaptive gait generation agree well with the data observed from biological experiments of the cats.

It should be noted, that the meaning of the term "adaptation" used here is much narrow than the general representations of the legged robot, for example to walk on complex ground or to change dramatically the relative leg phase difference for the robot to shift from walking to trod and running. The biological experiments of horse gait pattern exchanges shown that the horse changes its gait to minimize the energy consumption with respect to the locomotion speed. The mechanical study of energy consumption based pattern transition of quadruped locomotion is reported in [8].

5. Energy Efficient Biped Locomotion

Among all legged locomotion, from the present limit knowledge of mathematics and system control theories that, dynamic control of biped locomotion is of most difficult because of its stability problem both in walking and body balancing, the impact switching et al.. It is then imaged that the control mechanism may also be very complex in human. Therefore, bio-mimetic study of biped locomotion is extremely important, not only from robotics but also from medical requirements on rehabilitation, diagnosis as well as making prosthetic legs.

Averagely, children should spend almost one year after birth for their stable standing, however, they can realize the biped walking only one week quickly after they can stand! This fact strongly supports an important fact that biped walking is never difficult for the health person. Even for a Parkinson's disease patient, who is reported to have difficulties for starting and stopping walking actions, the locomotion can still be performed well if we write the lines of steps on the ground for him/her.

Development of real time motion capture technologies largely extended our understanding of human biped locomotion. In these technologies, the force plate is usually used with the optical measurements to measure and calculate the subject's body motions, the joint forces as well as the body energy changes, respectively. Since the accelerations of the joint angles are calculated numerically using low passed filters, the calculated joint force and consequently the energy of walking could not be obtained precisely.

Based on above considerations, we have constructed our original dynamic motion capture system as shown in **Fig.7**. As usual optical motion capture system, our system uses 6 high-speed cameras to measure the positions of the points attached on the body of the subject. 8 force plates are set on the ground to measure simultaneously the contact force vectors between the foot and the ground. Meanwhile, 32Chs of accelerometers as well as 32Chs of EMG are used to measure the body accelerations and muscle activities during motions. The measurement results can be displayed online in real time by 3D CG. We are now also developing the software so as the measurement date can be used directly in 3D dynamic motion simulations.

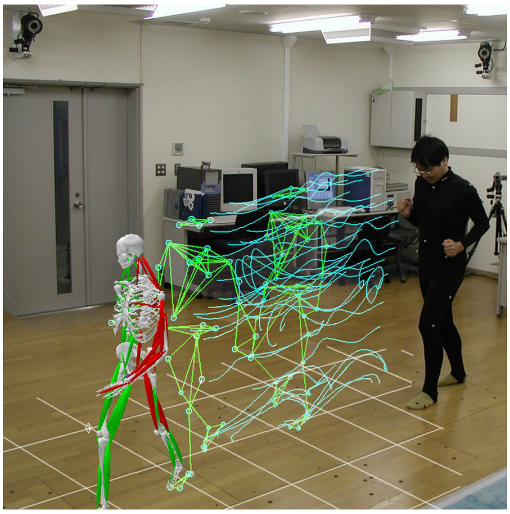


Fig.7 Dynamic Motion Capture System of BMC

The aim of our study on biped locomotion is to discover the robust, simple and energetically efficient control mechanism. From the simplicity point of view, we focused on the recent studies of passive dynamic walking, which never control the robot actively but only effects the initial potential

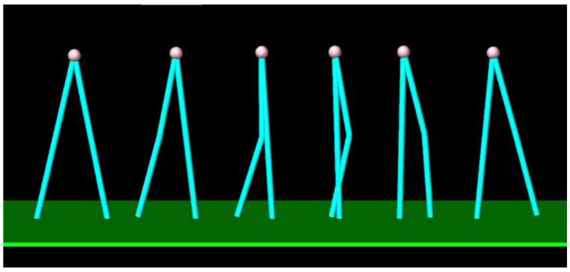
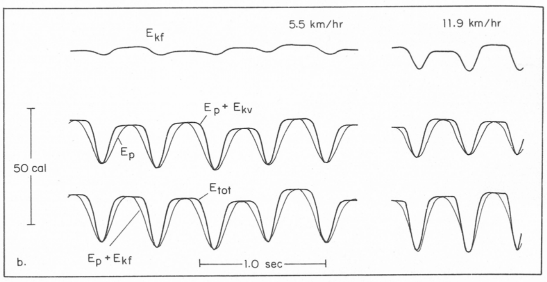


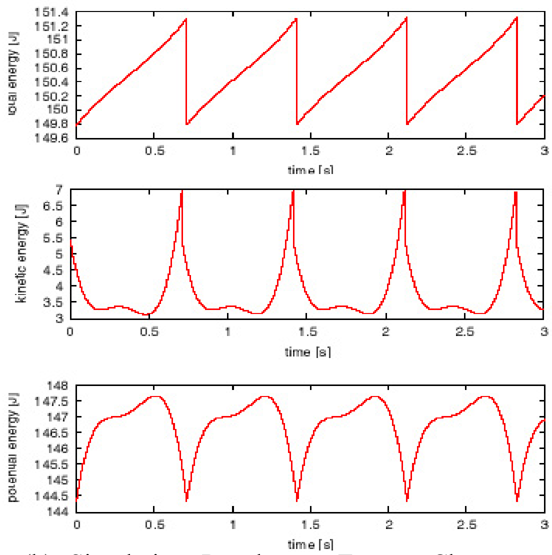
Fig. 8 Stick Diagram of Virtual Passive Dynamic Biped Walking on a level ground

energy and uses nature gravity force to compensate the energy loss at impact phase. We have proposed virtual passive dynamic walking by transforming the virtual gravity force, which is introduced toward the walking direction, to torque for the robot to walk on a level ground. This force is equivalent to the horizontal element of gravity for robot walking on a slope. The results are shown in **Fig.8**. From the energy consumption point of view, however, passive walking is energetically efficient only during the swing phase, which uses only the nature (or virtual) gravity force but is inefficient during impact phase. The comparison of energy profile between human and passive dynamic walking is shown in **Fig. 9**.



(a) Human Energy Changes of Biped Walking

(By Cavagna et al. 1976)



(b) Simulation Results on Energy Changes of Virtual Passive Dynamic Biped Walking

Fig. 9 Energy Change of Biped Locomotion

6. Conclusions

Bio-mimetic inspired researches towards better understanding and mechanical realization of diversity, adaptability as well as simplicity of legged locomotion control have been summarized. From Hexapod, Quadruped to Biped locomotion, because of the nonlinear dynamics, the redundant motion degree of freedoms as well as the discontinuous impact state transition, the nonholonomic constraints during jumping, the complete mathematical modeling, analyzing and designing of legged motion are still difficult. Nevertheless, the bio-mimetic approach can definitely richen and improve this field of researches. More information about our researches can be found in our homepage [12].

References

[1]F.A.Mussa-Ivaldi, S.F.Gister, 1992, "Vector field approximation: a computational paradigm for motor control and learning," Bio. Cybe., vol.67, pp.491-500.

[2]T. Odashima, Z.W. Luo, Y. Kishi, S. Hosoe, 2001, "Hierarchical control structure of a multi-legged robot for environmental adaptive locomotion," Proc. of CLAWAR 4th., pp.105-112.

[3]H.Tanaka, Z.W.Luo, T.Odashima, S.Hosoe, 2002, "Teaching of Locomotion for a Multi-legged Robot based on Sound Perception," Proc. of SICE Ann. Conf.,. WA17-3.

[4]T Odashima, H. Yuasa, Z-W Luo, M. Ito, 1999, "EmergentGeneration of Gait Pattern for a Myriapod Robot System Based on Energy Consumption," J. of RSJ, Vol.17, No.8, pp.1149-1157.

[5]S. Ito, H. Yuasa, Z.W. Luo, M. Ito and D. Yanagihara, 1999, "Development of Quadrupedal Robot Adapting to Environmental Changes," Adv. Rob. 13-3, pp.263-264.

[6]S. Ito, H. Yuasa, Z.W. Luo, M. Ito and D. Yanagihara, 1999,"Adaptive Locomotion to Periodic Perturbation: Adaptation Mechanism with Coupling of Oscillator and Link Dynamics," Artificial Life and Rob. 3, pp.97-101.

[7]S. Ito, H. Yuasa, Z.W. Luo, M. Ito and D. Yanagihara, 1998, "A Mathematical Model of Adaptive Behavior in Quadruped Locomotion," Biol. Cybe. 78, pp.337-347.

[8] S. Ito, H. Yuasa, K. Ito, 1996," Oscillator-Mechanical Model of the Pattern Transition on Quadrupedal Locomotion Based on Energy Expenditure" Trans. Of SICE, Vol.32, No.11, pp.1535-1543.

[9]F.Asano, M.Yamakita, Z.W.Luo, 2002, "Model Following Type PVFC for Variable Dynamic Bipedal Walking," Proc. of the ICASE/SICE Workshop -Intelligent Control and Systems-, pp.310-314.

[10]F.Asano, M.Yamakita, N.Kamamichi, Z.W.Luo, 2002, "A Novel Gait Generation for Biped Walking Robots Based on Mechanical Energy Constraint," Proc. of Int. Conf. on Intelligent Robots and Systems, pp.2637-2644.

[11]T.A. McMahon, 1984, "Muscles, Reflexes, and Locomotion," Princeton Univ. Press.

[12] http://www.bmc.riken.go.jp/~robot/index-e.html