Research Subject

Humanoid Walk Control using Central Pattern Generators with Discontinuous Phase Change (Tsuchiya Group)

(1) Goal and summary

A legged robot is a mechanical system composed of many links through rotational joints. The legged robot's locomotion is regarded as a rhythmic motion of a mechanical system with many degrees of freedom. Locomotion control of the legged robot implies control of such rhythmic motion. In some cases, a biped robot becomes unstable in attitude during locomotion. This type of locomotion is called dynamic locomotion.

This research is on the design method of a control system for a biped robot, with emphasis on the control for dynamic locomotion. Usually, the motion control of a mechanical system with many degrees of freedom is achieved by a model-based approach [1]. This kind of control system consists of a motion plan system and a motion control system. The motion plan system generates the nominal trajectory of the mechanical system, and the motion control system controls each joint to realize the nominal trajectory. Based on the model-based approach, the locomotion control system of the legged robot can be designed as follows. The motion plan system is composed of a family of periodic functions in which the nominal angular positions of the joints are encoded in such a way to achieve stable and periodic nominal locomotion. On the other hand, the motion control system is composed of a local feedback controller that controls the motors equipped at the joints receiving the nominal angular joint positions as commanded signals. This type of control system is neither always robust against disturbances nor able to adapt to variations in the environment.

There are two ways to overcome these difficulties. One is a method to modify the motion control system. This involves modifying the commanded signals by utilizing the signals of sensors such as an angular rate sensor, touch sensors equipped at the end of the robot's legs, etc. The other method is to modify the motion plan system. This involves designing the motion plan system as a dynamical system [2][3]. The nominal angular positions of the joints are encoded as states of the dynamic system. By inputting the signals of the sensors, the state of the dynamic system is changed according to the dynamic variances of the environment. As a result, the nominal locomotion, as well as the nominal angular position of the joints, are appropriately generated according to the variations in the environment.

The authors have been developing a control system for a biped robot by applying the latter method [4][5]. Our proposed control system is designed as follows. The motion plan system is composed of a motion generator and a trajectory generator. The motion generator consists of nonlinear oscillators, each of which has a stable limit cycle. The nonlinear oscillators have input signals from the touch sensors equipped at the end of the legs as well as mutual interactions with each other. As a result, each oscillator tunes a phase according to the variations in the environment. On the other hand, the trajectory generator generates the nominal values of the angular position of the joints as functions of phase of the corresponding oscillator. As a result, changing a locomotion pattern, the robot with the proposed controller can walk stably in a dynamic environment.

This report introduces our proposed control system for legged robots using nonlinear oscillator. As examples of this study, a biped robot is introduced, and the proposed control system is designed for the legged robot. The efficiency and performance of our approach are verified through numerical simulations and hardware experiments.

Mechanical Model

Here, we consider two types of biped robots shown in Figures 1 and 2. The first type of robot shown in Figure 1 consists of a body composed of four links and a pair of legs composed of six links. The other type of robot shown in Figure 2 consists of a body, a pair of arms composed of four links and a pair of legs composed of six links. In terms of the first type of robot, each link is connected to each other through a one degree of freedom rotational joint. Left and right legs are numbered as leg 1 and leg 2, respectively. The joints and the links of the body are enumerated as joint 1,2,3 and link 1,2,3 from the top. The joints and the links of legs are numbered as joint 1,2, $\cdots$, and link 1,2, $\cdots$ from the body to the tip of the leg.

In terms of the other type of robot, each link is connected to each other through a one degree of freedom rotational joint. The legs and arms are numbered in a similar manner as the first type of robot.

Both types of the robots have the same alignment of DOF(Degree of freedom) on legs. The first type of robot has three DOF(roll, yaw, pitch) on body, and by utilizing these DOF, it is able to control its attitude motion of the trunk. To the contrary, the other type of robot has no DOF on body. Therefore, it is not able to control its attitude motion of the trunk independently of the motion of the legs. This implies the motion of the legs is kinematically coupled with the attitude motion of the trunk. As a result, it is impossible to specify both gait pattern and attitude motion of the trunk independently. The attitude motion is controlled through controlling of joints of the legs.

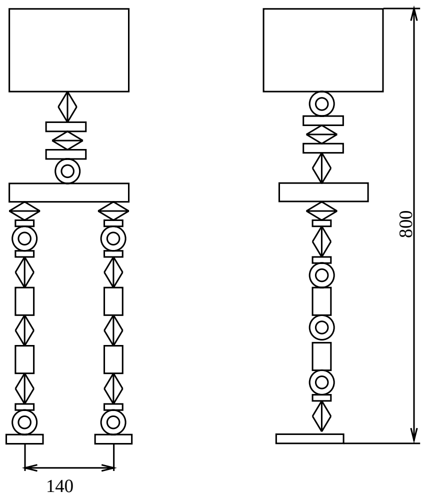

Figure 1: Schematic model of biped robot (1)

Locomotion Control

The architecture of the proposed control system is shown in Figure 3. The control

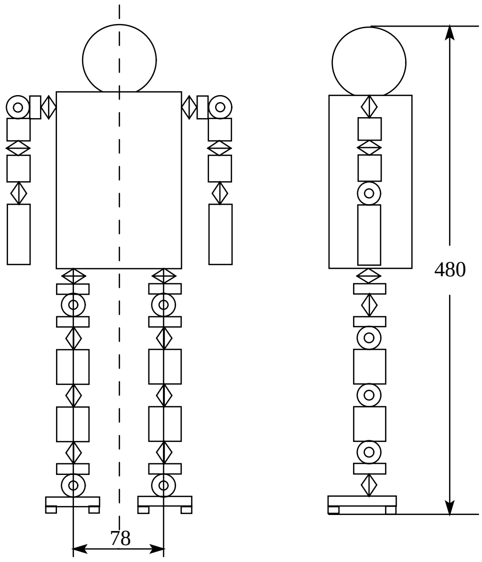

Figure 2: Schematic model of biped robot (2)

system is composed of a motion plan system and a motion control system. The motion plan system is composed of a motion generator and a trajectory generator. Nonlinear oscillators in the motion generator tune the phases through mutual interactions and the feedback signals from the touch sensors. The trajectory generator encodes the nominal trajectory of each joint angle in terms of phase of the oscillators, which is given to the motion controller as the commanded signal. The motor controllers in the motion control system drive all the joint motors so as to realize the desired motions that are generated by the motion plan system.

The motion of the biped robot is determined by specifying the motions of the tips of the two legs and two arms as well as the attitude motion of the body. The motion generator is composed of two kinds of nonlinear oscillators (Figure 4). One is a set of motor oscillators, which correspond to the motions to be specified. Another is a set of inter-oscillators that connect the oscillators. Five motor oscillators corresponding to the legs', arms' and body's motion and one inter-oscillator compose the network for the biped robot. The motion oscillators encode the trajectories of the corresponding motions in terms of their phases. The nominal trajectory of the tip of each leg is designed for the biped robot as follows. Two trajectories are given: One is the nominal trajectory for the swinging phase, and the other is that for the supporting phase (Figure 5). For the tip of leg i, two typical points, $r^{(i)}_{AEP}$, anterior extreme position (AEP) and $r^{(i)}_{PEP}$, posterior extreme position (PEP), are defined relative to the body. The trajectory for the swinging phase $\eta^{(i)}_{Sw}$ is a closed curve involving AEP and PEP. On the other hand, the trajectory for the supporting phase $\eta^{(i)}_{Sp}$ is a line connecting AEP and PEP. These two trajectories are switched at AEP and PEP. This involves switching from the swinging phase to the supporting phase at AEP and from the supporting phase to the swinging phase at PEP. Moreover, for the biped robot, the nominal trajectories of the arms and the body are given as closed curves in terms of the phases of the corresponding motor oscillators. In the motion generator, the angle of each joint is calculated from these nominal trajectories by

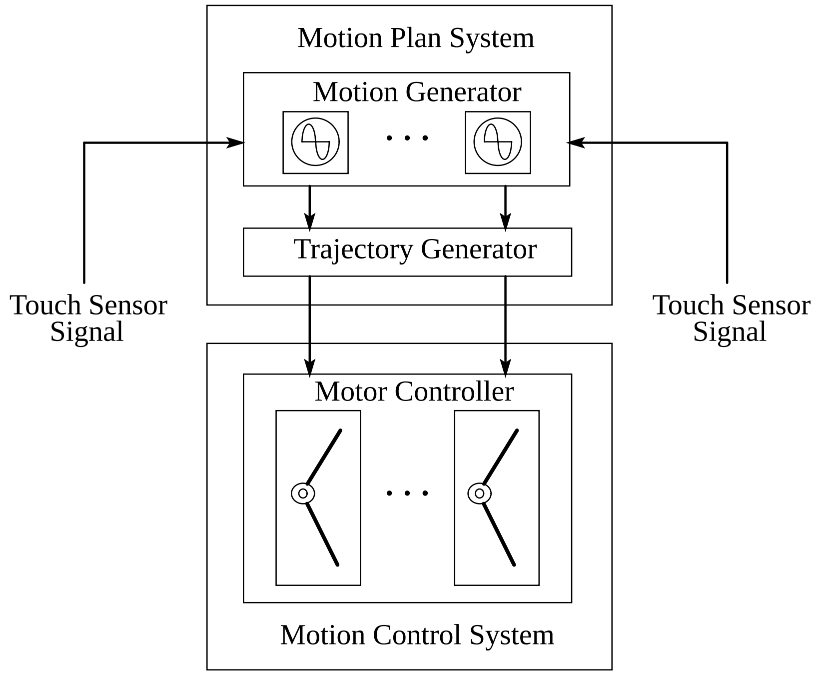

Figure 3: Architecture of Locomotion Control System

means of the inverse kinematics. The angles of the joints are given to the motion controller as the commanded signals.

The nominal trajectory of attitude motion of the trunk is designed for the biped robot as follows. The nominal trajectory of attitude motion of the trunk is given as a function of the phase of the inter-oscillator. In terms of the attitude motion of the trunk in pitch axis, there are three control parameters: the amplitude of the nominal attitude motion, the phase difference between the motion oscillator and inter-oscillator, and offset value in the attitude. Furthermore, in terms of the attitude motion of the trunk in roll and yaw axes, there are two control parameters: the amplitude of the nominal attitude motion, and the phase difference between the motion oscillator and inter-oscillator.

The dynamics of the oscillators in the motion generator is designed as follows. A phase dynamics is used for the design of the oscillator network [6].

$$\dot{\phi}^{(i)} = \omega + g^{(i)} \tag{1}$$

where $\phi^{(i)}$ is a phase of oscillator i, ω is an angular velocity of the oscillator and $g^{(i)}$ is an influence term from other oscillators and an environment. Each oscillator has mutual interactions with other oscillators (Figure 4). In the cases of the biped robot, each motor oscillator corresponding to a leg's motion has mutual interactions with the inter-oscillators. Moreover, each motor oscillator corresponding to an arm's motion and the attitude motion of the body receive unidirectional influence from the inter-oscillator. These interactions form an inherent phase relationship among the oscillators, and then, an inherent locomotion pattern emerges.

On the other hand, each oscillator corresponding to the leg motion receives a sensor signal of the touch sensor equipped at the tip of the leg as a feedback signal. As soon

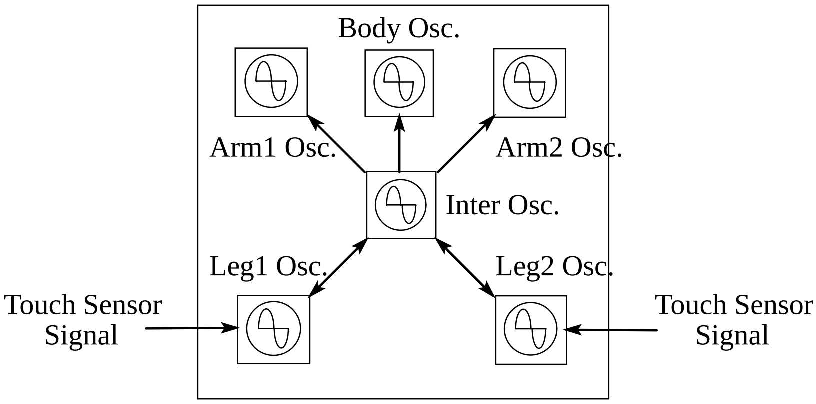

Figure 4: Motion Generator

as the touch sensor signal inputs to the oscillator, the phase of the motor oscillator shifts to the value corresponding to that at the AEP in the nominal motion. At the same time, the trajectory changes from that of the swinging stage to that of the supporting stage. This means that, by using the feedback signal from the touch sensor, the oscillator tunes the phase according to the variations in the environment. This also leads to variation of commanded signals from the motion generator to the motion controller. As a result, the legged robot achieves an adaptive locomotion pattern to cope with variations in the environment.

Numerical simulation

Numerical simulations are implemented to verify the performances of the proposed control system, with emphasis on the robustness of steady locomotion against the variation in the environment. The model of the robot shown in 2 (HOAP-1) is used as the simulation model.

The nominal trajectories of all the joints are determined so that the biped locomotion robot can walk stably in a certain fixed environment. In order to verify the effectiveness of the proposed control system, the simulations of the model-based control system without phases tuning (conventional) are also investigated. As a change of the environment, changing the nominal stride changes the nominal locomotion speed. The results are shown in Figure 6. This figure shows the period of locomotion, the interval between the times when the left leg makes contact with the ground. From this figure, it is revealed that the robot with the proposed control system can walk in a wide velocity region by changing the period of the locomotion. From this result, it is confirmed that by using the feedback signal from the touch sensor, the oscillator tunes the phase according to the variations in the locomotion speed, and this also leads to variation of commanded signals from the motion generator to the motion controller. As a result, the legged robot achieves an adaptive locomotion pattern to cope with variations in the locomotion speed.

Hardware experiment

Performance of the proposed control system is verified also by hardware experiments using two types of hardware model: The first one is HOAP-1(made by Fujitsu Automation

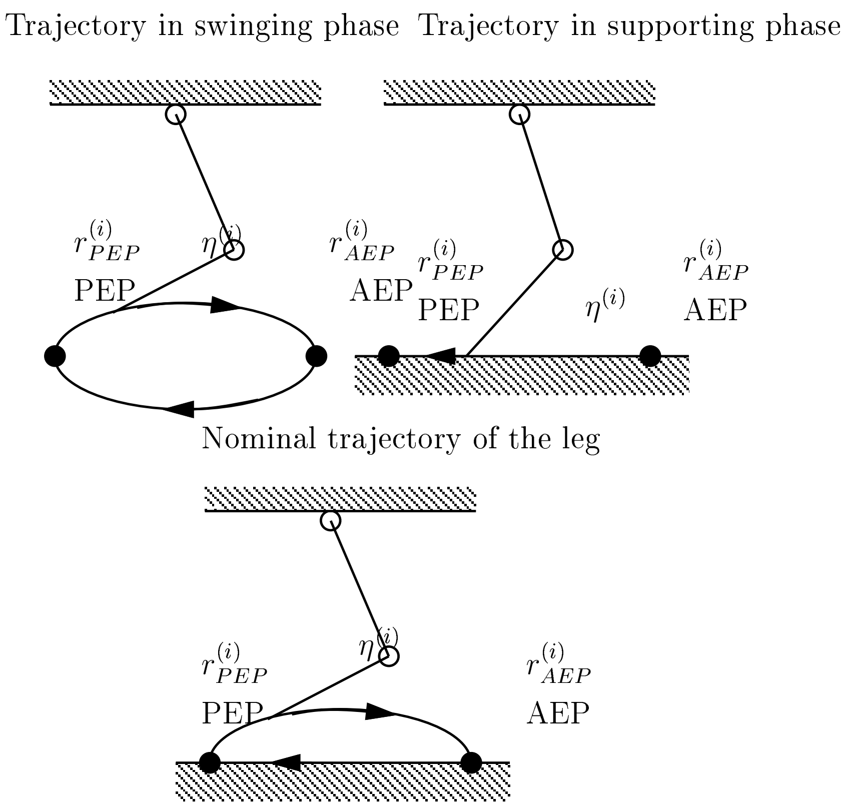

Figure 5: Trajectory of the leg

Co. Ltd.) and the other is the biped robot we developed.

• **The architecture of hardware equipment with HOAP-1**

Figure 7 shows the photograph of another hardware model of biped robot. The CPU of the host PC (Personal computer) is Celeron 1GHz and operating system (OS) is Realtime Linux. Host computer and the robot are connected through USB. Host computer is used for the debugger and signal monitor. The control program runs on the host computer. The intelligent motor drivers are equipped on the robot to control all the joints by local feedback. The commanded signals of the joint angles are given to the drivers. The force sensor signal is fed back to the host computer through A/D converter.

Hardware experiment 1

The nominal locomotion speed is changed gradually by changing the nominal stride. The results are shown in Figure 8. This figure shows the profiles of the period of inter-oscillator.

From this figure, it is shown that the robot with the proposed control system can walk adaptively to the variation of the environments by tuning the period of the locomotion. This result is almost corresponding to the results of the numerical simulations.

• **The architecture of the developed hardware equipment**

Figure 9 shows the photograph of the hardware model of biped robot. Figure 10 shows the block diagram of the hardware model. The CPU's of the host PC(Personal computer) and the on-board controller are Pentium III 1GHz and Pentium III 850MHz, respectively. Operating systems (OS) of both computers are Realtime Linux. Host computer and controller are connected through 100BASE-TX network. Host computer plays roles of debugger and signal monitor. The control program runs on the controller. The controller receives joint angle of the motor through encoder counter. The commanded signals are given to the motor through motor driver. The force sensor signal is fed back to the controller through A/D converter (see appendix in detail).

Hardware experiment 2

Figure 11 shows the locomotion period of biped robot. The figure shows that the robot with the proposed control system establishes steady locomotion for both duty ratio $\hat{\beta} = 0.50$ and $\hat{\beta} = 0.70$.

Figure 12 shows the time history of the reaction force at the tip of the left leg. The figure indicates that the robot has no huge shock forces at the instance of contact or bounding forces.

(2) Results and their importance

This research is on the design method of a control system for a biped robot, with emphasis on the control for dynamic locomotion. Usually, the motion control of a mechanical system with many degrees of freedom is achieved by a model-based approach. This kind of control system consists of a motion plan system and a motion control system. The motion plan system generates the nominal trajectory of the mechanical system, and the motion control system controls each joint to realize the nominal trajectory. This type of control system is neither always robust against disturbances nor able to adapt to variations in the environment.

There is a way to overcome these difficulties. The method is to modify the motion plan system. This involves designing the motion plan system as a dynamical system. The nominal angular positions of the joints are encoded as states of the dynamic system. By inputting the signals of the sensors, the state of the dynamic system is changed according to the dynamic variances of the environment. As a result, the nominal locomotion, as well as the nominal angular position of the joints, is appropriately generated according to the variations in the environment.

The authors have been developing a control system for a biped robot by applying this method. Our proposed control system is designed as follows. The motion plan system is composed of a motion generator and a trajectory generator. The motion generator consists of nonlinear oscillators, each of which has a stable limit cycle. The nonlinear oscillators have input signals from the touch sensors equipped at the end of the legs as well as mutual interactions with each other. As a result, each oscillator tunes a phase according to the variations in the environment. On the other hand, the trajectory generator generates the nominal values of the angular position of the joints as functions of phase of the corresponding oscillator. As a result, by changing a locomotion pattern, the robot with the proposed controller can walk stably in a dynamic environment.

This report introduced our proposed control system for legged robots using nonlinear oscillator. As examples of this study, a biped robot was introduced, and the proposed control system was designed for the legged robot. The efficiency and performance of our approach were verified through numerical simulations and hardware experiments.

References

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[6] Kuramoto Y., Chemical Oscillations, Wave and Turbulence, Springer, Berlin, 1984.

Appendix

Hardware spec of the developed robot

Mechanism

The developed biped robot has 6 DOF for each leg and 3 DOF for body. Each joint is designed as module. Each joint module is connected through structure members and composes the whole system. The top part of the body (breast) is the housing of the electrical circuits such as controller, motor drivers, D/A converters, etc. The range of motion at each joint is shown in the following table.

Joint name	Range of motion ([deg])
Trunk pitch axis	$\pm$ 20
Trunk yaw axis	$\pm$ 30
Trunk roll axis	$\pm$ 20
leg joint 1 (yaw)	$\pm$ 45
leg joint 2（roll）	$\pm$ 30
leg joint 3（pitch）	Forward 60, Backward 60
leg joint 4（pitch）	Forward 0, Backward 120
leg joint 5（pitch）	Forward 60, Backward 60
leg joint 6（roll）	$\pm$ 30

Actuator module

Each actuator module is composed of motor, harmonic drive gear and optical encoder. The driving force of the motor is transferred to the harmonic gear through pulley-belt system. The spec of each element is summarized in the following table.

Elements	Spec	Model No.	Vendor
Motor	typ.18 [W]	NC-256401	Chiba Precision Co. Ltd.
Gear	Gear ratio 110:1	FB-14-110-2-R	Harmonic Drive Systems, Inc.
Encoder	500 [P/R]	OME-500-2MCA	Nidec Nemicon Corp.

Sensors

As external sensors, force sensors are equipped on the robot to detect the contact of the leg on the ground. Four loadcells made by Kyowa Electronic Instruments Co. Ltd. (Model No.:LM-20KA, Typ. measurable load: 200[N]) are equipped on the underside of each foot.

D/A Converter board

The developed biped robot has many DOF. The D/A converter board, which sends commanded signal from the host PC to the motor drivers, is required to have many channels and downsizing. We developed the D/A converter boards to satisfy the requirements. The spec of the developed D/A converter board is shown in the following table.

Item	Description
Board size	80 [mm] × 100 [mm]
Channel No.	8 [CH/board]
Resolution	12 bit
Range	0 ∼ 10 [V], -5 ∼ 5 [V] Selectable on each CH
IC	Analog Devices Inc. AD7247AAR
Interface	PC104 Bus subset

Counter board

The developed biped robot has many DOF. The counter board, which sends measured signal of the joint angles from the encoders to the host PC, is required to have many channels and downsizing. We developed the counter boards to satisfy the requirements. The spec of the developed counter board is shown in the following table.

Item	Description
Board size	80 [mm] × 100 [mm]
Channel No.	8 [CH/Board]
Range	24 bit
IC	Cosmo Techs Co. Ltd. PCC130
Interface	PC104 Bus subset

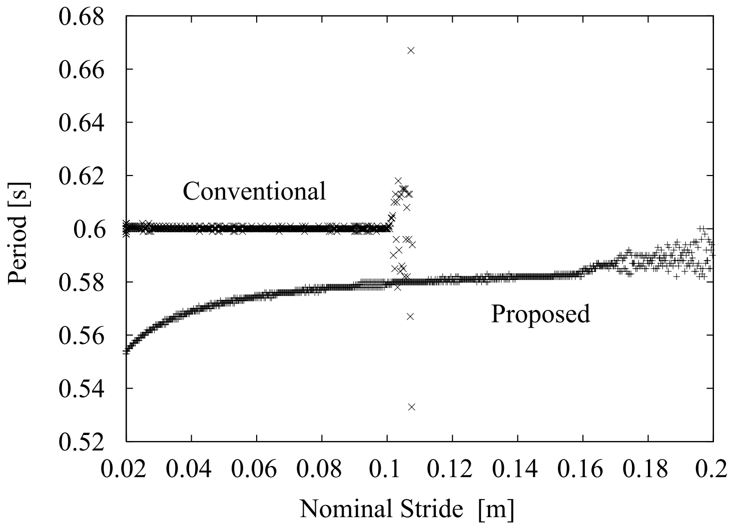


Figure 6: Period of locomotion

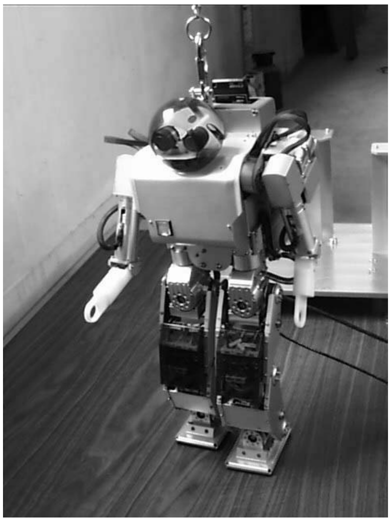


Figure 7: Hardware model of biped robot, HOAP-1 (Fujitsu Automation)

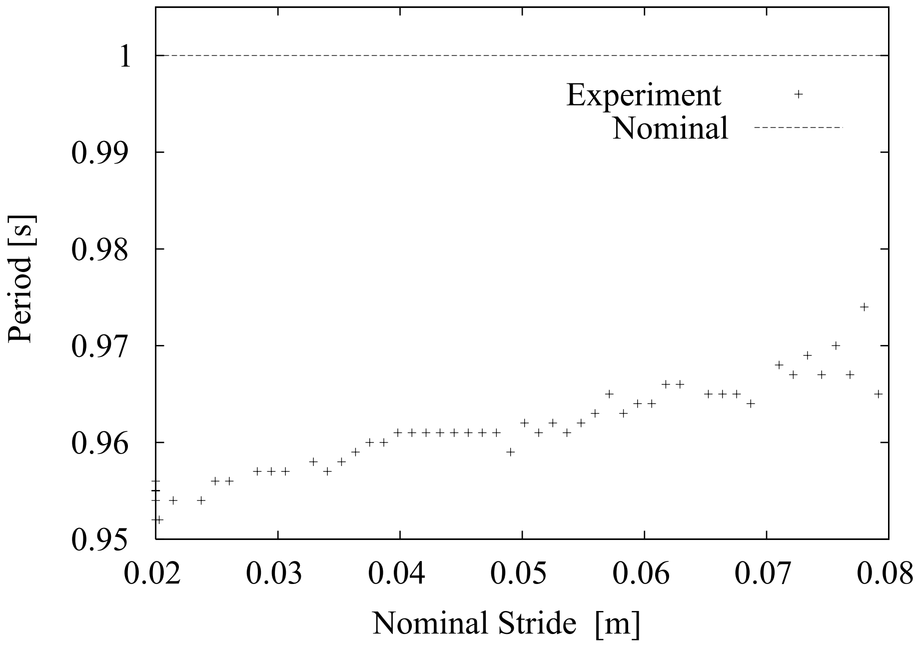


Figure 8: Period of locomotion

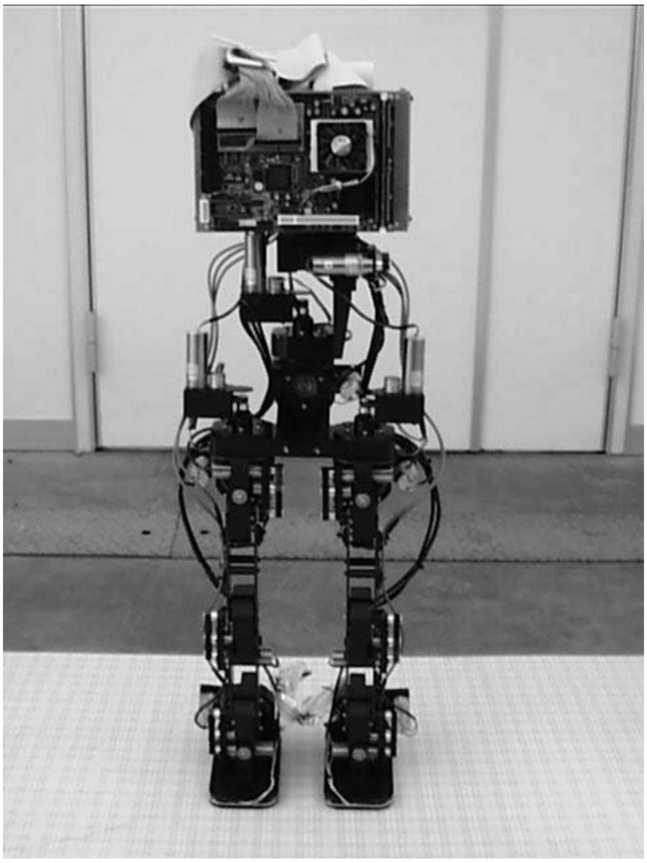


Figure 9: Hardware model of biped robot

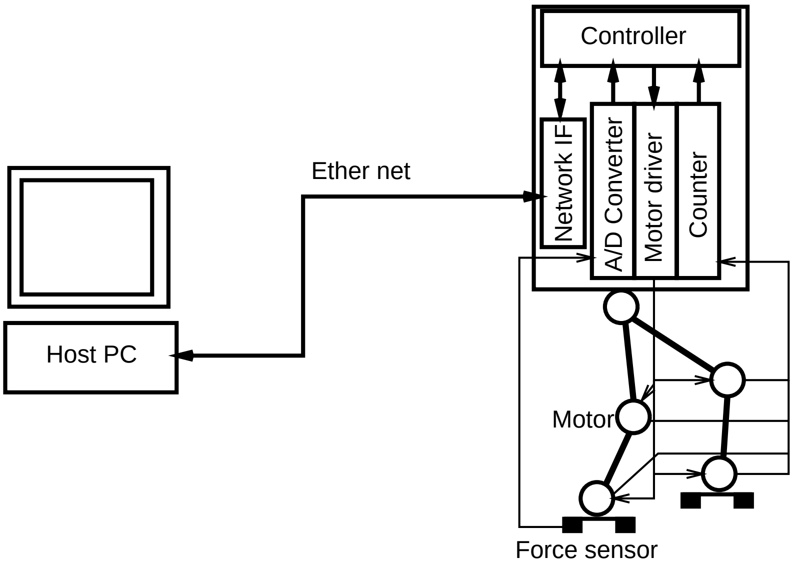
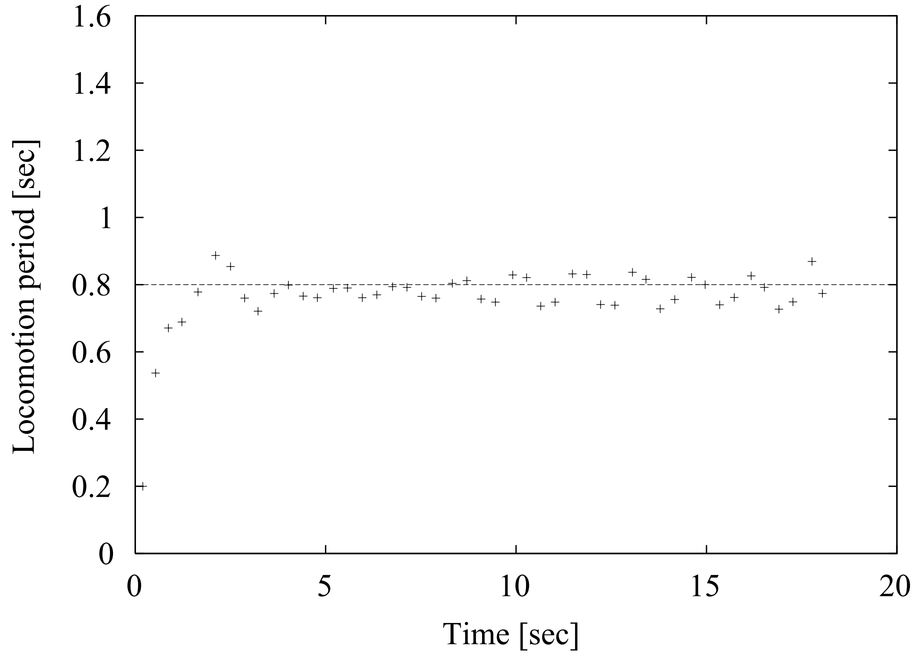
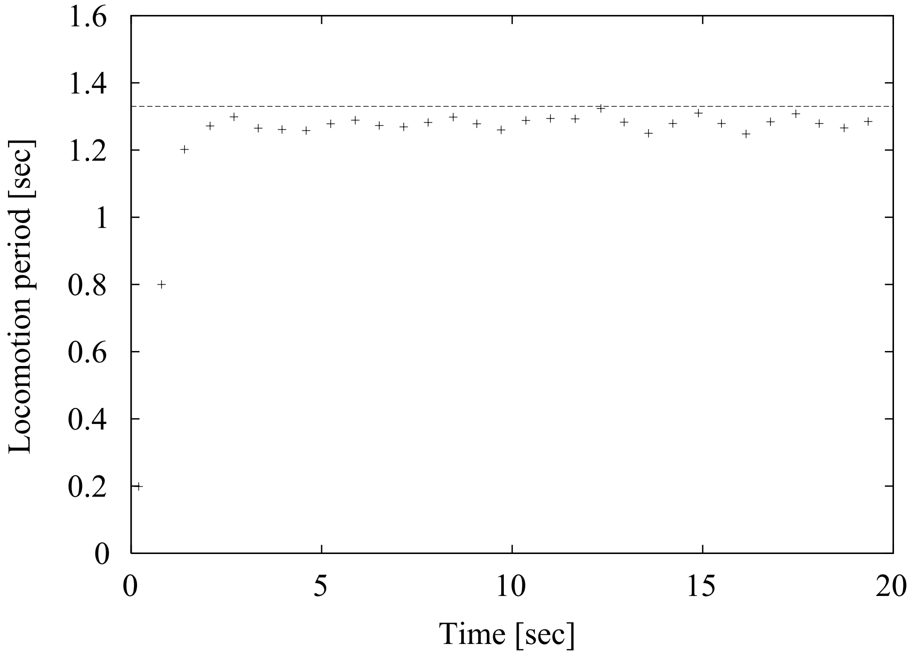


Figure 10: Block diagram of the hardware model

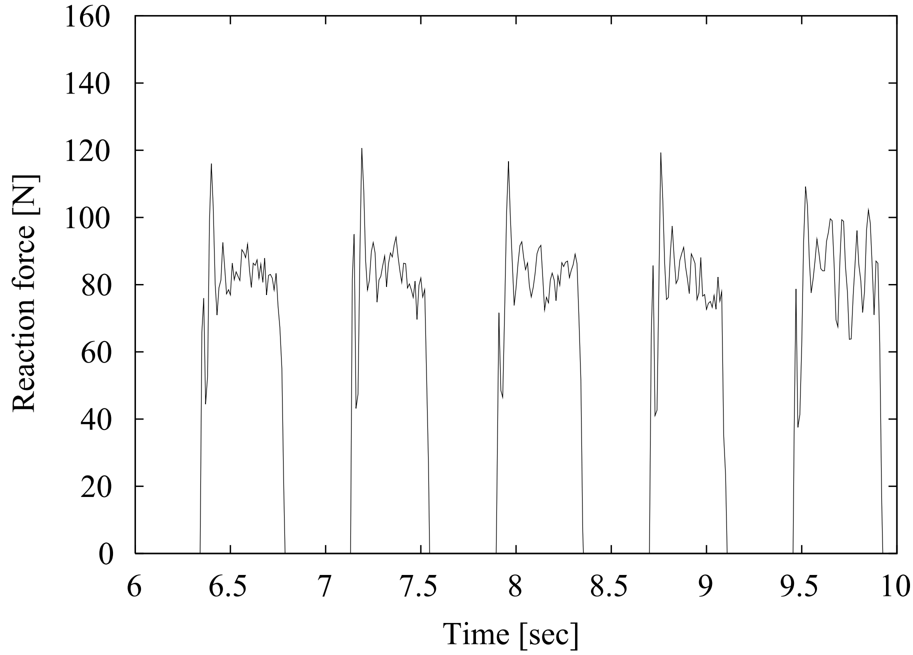


(a) $\beta = 0.50$

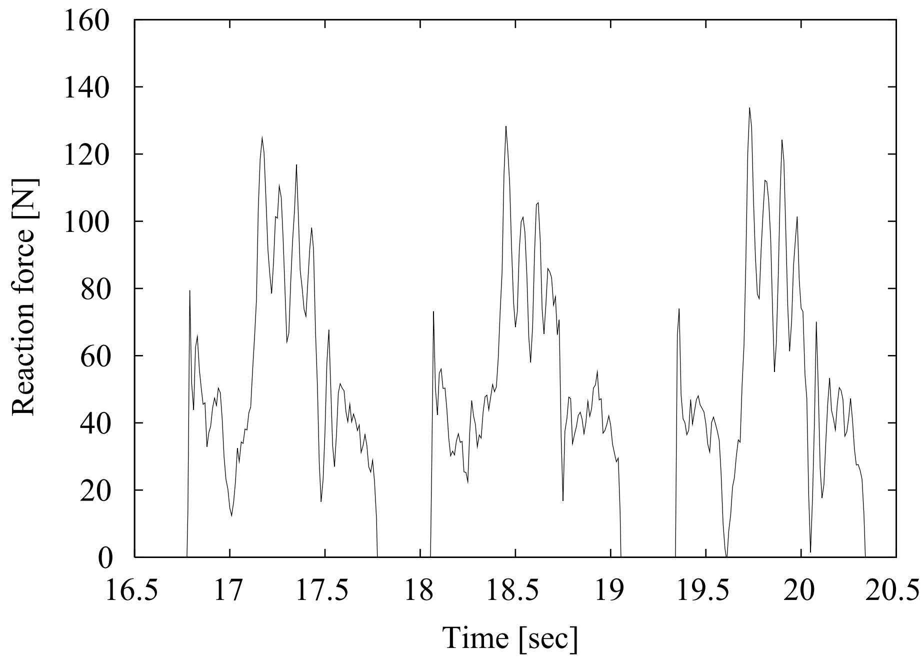


(b) $\beta = 0.70$

Figure 11: Period of locomotion



(a) $\beta = 0.50$



(b) $\beta = 0.70$

Figure 12: Time history of reaction force