Locomotion Control of 7-Linked Walking Robot Embedded with CPG Using Neural Oscillator

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***Abstract*—In this paper, as a control method of a biped walking robot, an adaptive Central Pattern Generator (CPG) using Hopf oscillator whose output can be synthesized by teaching signal is designed. Also, the adaptive CPG with teaching signal are tested on both computational model and experimental system of seven-linked planner biped robot developed in this research. Furthermore, in order to achieve human-like stabilized walking, sensory feedbacks of upper body posture angle and foot force information are implemented to the controller. In the end, the effect of the sensory feedback on stabilizing the walking motion is investigated through experimental works.**

***Index Terms*—Biped Walking Robot, Semi-Passive Walking, Central Pattern Generator, Hopf Oscillator**

I. INTRODUCTION

RECENTLY, numerous studies related to various kinds of legged walking robot have been actively carried out. Among them, biped walking robot field shows rapid and outstanding advances. Also, for realizing human-like walking of biped robot systems, human locomotion has been investigated continuously. Human locomotion is based on the pendulum-like motion utilizing gravity and its own stabled area even though inverted posture on the ground. This walking method based on pendulum-like motion utilizing only gravity is referred as passive walking [1]. It shows greatly good performance in energy efficiency [2], however cannot walk on the level ground. Therefore, semi-passive walking robots utilizing the pendulum theory with minimal number of actuators have been considered in previous research works [3]. Besides, various methods of generating the locomotion for semi-passive walking robots have been proposed [4, 5].

For usual locomotion on the flat ground, human beings intuitively generate patterned motion of both legs with little or no high-level control by brain. The motion looks like a habitual and rhythmic pattern optimized by learning accompanied with growth. It means that the periodical locomotion of biological systems is usually governed by neuro pattern generator at spinal level, though can be also controlled by brain. This is the fundamental basis for this and other most researches related to CPG control [6, 7]. However, the bipedal system becomes more complicated, the more intelligent nervous system CPG is required for the controller. Therefore, a locomotion control method of CPG using a neural network structure and neural oscillator which mimics a human nervous system structure has been actively studied in recent years [8, 9, 10]. Among them, CPG using Hopf oscillator is drawing attention as a pattern generator capable of modulating more various types of rhythmic locomotion [11]. However, few experimental study of semi-passive 7-linked biped robot embedded with CPG of Hopf oscillator using upper body posture angle and foot force information as state feedback has been observed.

Therefore, in order to realize the human-like intuitive locomotion of biped robot, adaptive CPG using Hopf oscillator with sensor feedbacks for generating balanced walking motion was constructed. Then, it was tested through computer simulations and experimental works by using a new biped walking robot developed in this research.

II. DEVELOPMENT OF 7-LINKED BIPED ROBOT

A. Mechanism Design of Biped Robot

The biped robot developed in this study is displayed in Fig. 1. It is a 7-linked planner robot system whose motion is restricted to the vertical plane. Two parallel plates were installed vertically on the upper body in order to constrain its lateral motion. During experiments, two horizontal bars are positioned between the plates so that the robot body cannot move laterally. The robot's height is 0.9 [m], the length of each legs is 0.6 [m], the width of the robot is 0.18 [m] and the total weight is 2.0 [kgf], respectively. The robot was equipped with four servo motors (Robotis co., Dynamixel XM430-W210-T) as main actuators to rotate each leg back and forth. The other motors attached on ankle joints assist lifting up and landing down of each foot link. The output torque of the motor is 3.0 [Nm] and its power consumption is 27.6 [W]. Motors of small size were employed to realize the energy efficient semi-passive walking. So the joints have enough backdrivability to be rotated easily by the gravity force when the motor torque is not applied. Also, two smaller servo motors (Robotis co., Dynamixel AX-12A) were equipped at the upper part of the knee joint to assist bending and stretching motion of each knee joint. The output torque of the motor is 1.5 [Nm] and its power consumption is 18 [W]. A microcontroller board (STM32F3discovery, STMicroelectronics co.) equipped with inertial sensor components for measuring posture was installed on the upper

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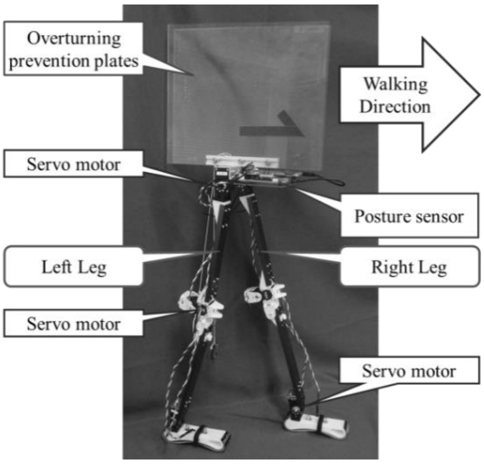

Fig. 1. Biped robot developed in this research

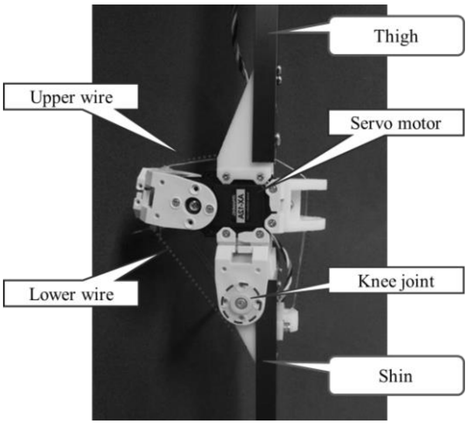

Fig. 2. Knee joint of biped robot

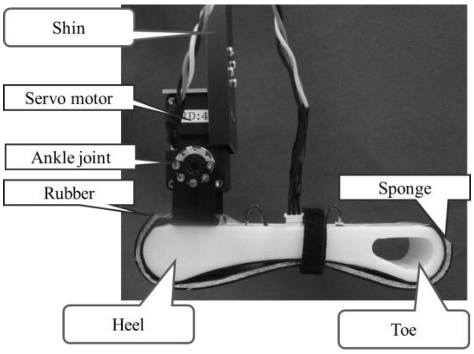

Fig. 3. Foot part of biped robot

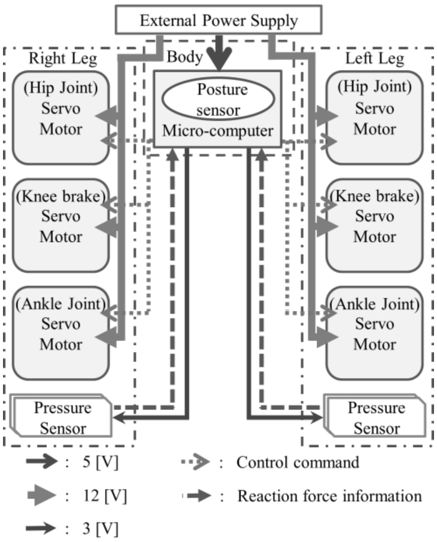

Fig. 4. Configuration of control system of biped robot

body as a main controller.

In this study, the knee joint of the biped robot was designed as a free axis to exploit the characteristics of passive walking. The knee part of the developed biped robot is displayed in Fig. 2. It has no motor at the joint itself, but its motion is assisted by the servo motor installed at its upper part during walking motion. The servo motor keeps the knee stretched and fixed while the leg is in stance phase, and supports bending motion while the leg is in swing phase. The motor torque for assisting the locking and bending motion is transferred by two wires. The upper wire connecting the link of the servo motor to the front side of shin link is used for stretching and locking the knee joint as stretched like the human body, while the lower wire connecting the link of the servo motor to the back side of shin link is used to assist bending the knee joint respectively. The lengths of both wires are a little longer than the required. Therefore, they have margin and are not always stressed by the servo motor. Moreover, the shin link can move freely during swing phase so that the pendulum dynamics could be utilized as possible.

Fig. 3 shows the foot part of the developed biped robot. Size and parameter of the foot are referring on the computational model of the previous research [12]. Where the length of the foot is 148 [mm], the height of the ankle joint from the sole is 55 [mm], and the heel is located in 15 [mm] backward from the ankle joint. The radius of arc shape parts at toe and heel is 15 [mm], thus the distance between the centers of toe and heel arcs is 118 [mm]. The foot part is made of plastic material with a 3D printer. Two pressure sensors were attached on the surface of heel and toe parts respectively. Those are covered by sponge and rubber layers that were used to get stable force signal from pressure sensors by reducing noisy signals due to grounding impact and noisy signals. Therefore, the contact condition of the foot, i.e., which part contacts with the ground or how much the reaction force is, can be measured with the foot sensors. The servo motor at the ankle joint rotates and keeps the foot as lifted-up in swing phase to avoid colliding to the ground. In stance phase, the foot is kept in horizontal state, respectively.

B. *The Configuration of the Control Hardware*

Fig. 4 shows the configuration of the control system of the developed robot. The microcomputer computes the pose angle of the robot upper body information and the foot force information. Based on the information, it calculates the motion control commands and sends them to all motors through communicational channel. The sampling time for every computation was set to 60 [ms] in this research. A little slow sensory feedback than a general humanoid robot was used in the developed system. The electric power for the embedded controller and the motors are supplied from an external power supply or a battery pack equipped on the robot body.

III. DESIGN OF ADAPTIVE CPG CONTROLLER USING NEURAL OSCILLATOR WITH TEACHING SIGNAL

A. *Adaptive CPG Controller Using Neural Oscillator*

It has been reported that CPG plays important role of generating and controlling rhythmic locomotion of biological systems such as human beings and animals. CPG generates a constant pattern in the state of no internal input, but if there is, it makes various patterns by responding sensitively to them. Posture angle and the foot force information of biped robot were set as the external input for CPG, in order to generate the rhythm to stabilize the bipedal walking motion in this study. Where, neural oscillator based on adaptive Hopf oscillator is employed [11]. This oscillator can learn and adapt to any kind of periodic teaching signal. Even if a teaching signal composed with multiple frequency component, the oscillator is capable to adapt to the closest frequency of own natural frequency. By connecting multiple oscillators as a network structure described in Fig. 5, an adaptive CPG which can adapt the complicated teaching signal composed with multiple frequency is constructed. The learned signal obtained by a network is the sum of outputs from all the oscillators which are multiplied by the weight constant depend on each oscillator.

The adaptive CPG controller of the robot is designed as a network structure of adaptive Hopf oscillators including additional signals of internal and external sensory feedbacks [13]. The set of equations describing an adaptive CPG are given as follows:

$$\dot{x}_i = \{\gamma(\mu^2 - \mathrm{r}_\mathrm{i}^2)x_\mathrm{i} - \omega_i y_i + \epsilon F + \tau \sin(\theta_i - \Phi_i) + (g_S H_j + g_e \psi)\frac{x_i}{r_i}\}(1 - S_n). \tag{1}$$

$$\dot{y}_i = \{\gamma(\mu^2 - \mathrm{r}_\mathrm{i}^2)y_\mathrm{i} + \omega_i x_i + (g_S H_j + g_e \psi)\frac{y_i}{r_i}\}(1 - S_n). \tag{2}$$

$$\dot{\omega}_i = -\epsilon F \frac{y_i}{r_i}. \tag{3}$$

$$\dot{\alpha}_i = \eta x_i F. \tag{4}$$

$$\dot{\Phi}_i = \sin\left(\frac{\omega_i}{\omega_0}\theta_0 - \theta_i - \Phi_i\right). \tag{5}$$

$$\theta_i = \mathrm{sgn}(x_i)\cos^{-\Delta}(-\frac{y_i}{r_i}). \tag{6}$$

Where x and y are the state variables, ω is frequency of oscillator, μ is amplitude of oscillator, γ is the positive constant that adjusts the convergence speed to the limit cycle and the steady state of oscillator, F is the perturbing input signal, subscript i denotes the number of the i^{th} oscillator, subscript j denotes the number of the j^{th} oscillator group, respectively. This oscillator will learn and adapt the frequency to the perturbing input signal by converging ω to the frequency of F. Where ϵ is the coupling constant to the input signal, τ is weight constant between another oscillator, α is the amplitude of the oscillator, Φ is variable of the phase difference between the oscillator i and the reference oscillator 0. Internal and external feedback signals are tuned by the gains g_S and g_e. As an internal feedback, high level control signal H composed with teaching signal is use as reference signal of the oscillators. Where ψ is the upper body posture angle of the robot, used as one of the external feedback. Where S is the binary variable to stop the phase modulation according to the foot reaction force information [13]. The variable S will be activated as one in following two cases. The first case is when there is no foot force signal while the leg is about to start the stance phase. The second case is when the foot force signal still exists while the leg is about to start the swing phase. Where the subscript n becomes r or l respectively, i.e. represents r is right leg and l is left leg.

B. Teaching Signals and Oscillators Network Structure

The adaptive CPG controller requires teaching signals to learn as basic waveform. Therefore, teaching signals for the hip joint and knee joint are generated by referring the resultant motion signals given in the reference paper [13]. In addition, a signal for the ankle joint was newly designed. Fig. 6 shows the developed teaching signals. Where $State_1$, $State_2$ and $State_3$ are for hip, knee, and ankle, respectively.

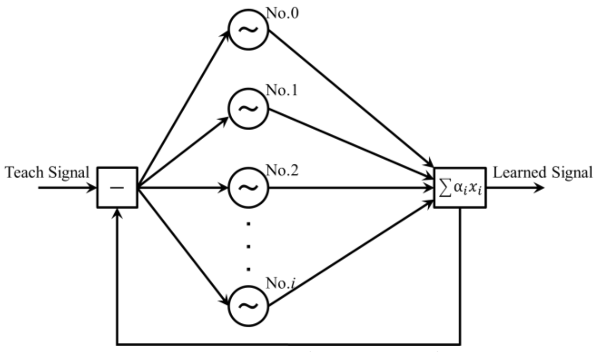

Fig. 5 Network structure of adaptive Hopf oscillators

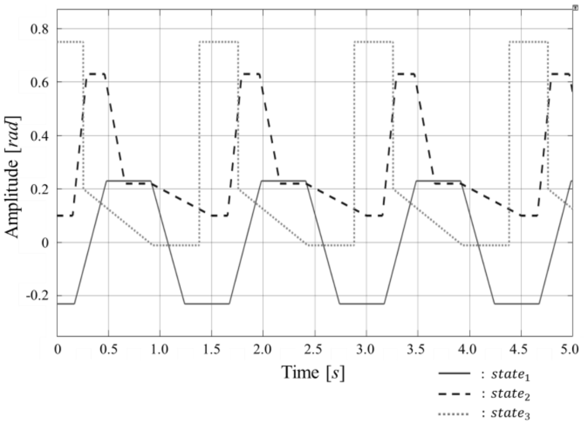

Fig. 6 Teaching signals for each oscillators

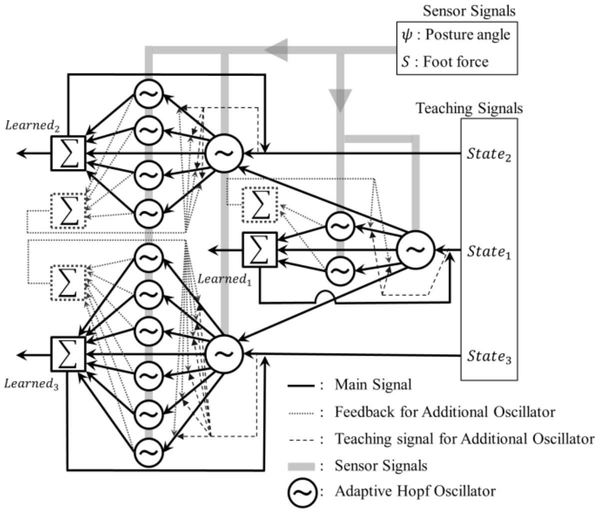

Fig. 7 Network structure of CPG controller with adaptive Hopf oscillators

The schematic diagram of network structure of CPG controller with adaptive Hopf oscilators is depicted in Fig. 7. In order to keep timing of each leg, one component of signal generated at the oscillator of hip joint is used as one input of the primary oscillator for each oscillator group. Also, the primary oscillator receives the learned signal as feedback. At the same time, the learned signal generated without primary oscillators signal is given to the additional oscillators as feedback. Every oscillator recieves the teaching signal as an input.

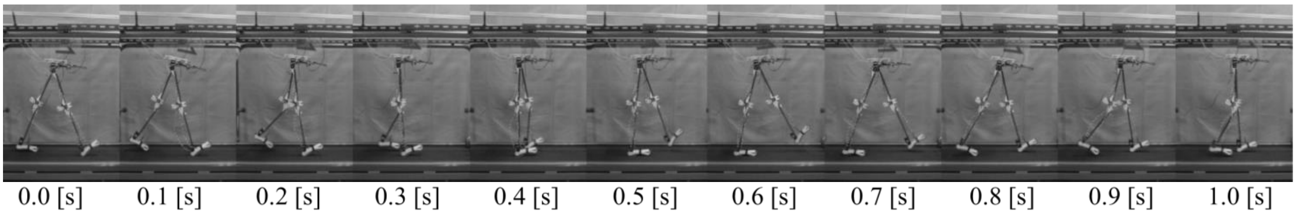

Fig. 8 Experimental result of walking motion of the biped robot embedded with CPG control with feedback signals

C. Control Method of the Biped Robot Using CPG

The target angle as motion command for each joint can be calculated by the following equation:

$$\varphi_{nm} = g_{Am}L_j + B_m. \tag{9}$$

Where, g_A and B_m are the gain and bias of the learned signal, *L* is the learned signal from the oscillator group. Where the subscript *m* becomes *H* for hip joint, *K* for knee joint, and *A* for ankle joint, respectively.

IV. IMPLEMENTATION OF CPG CONTROLLER FOR WALKING ROBOT

A. Application to Computational Model of Walking Robot

In order to verify the adaptive CPG using proposed teaching signals, walking simulation has been carried out with 7-linked biped walking robot model in computational environment [12]. Calculation has been performed in *Matlab R2016b*/Simulink environment. “ode4 of Runge-Kutta” with fixed time step was employed as numerical integration algorithm where its sampling time is set as 0.001 [sec]. In this calculation, no feedback signals of the robot was implemented to the controller, namely open-loop control was used.

Firstly, the parameters were tuned and identified by trial and error method. The parameters were set resultantly as follows; gain g_{AH} and bias B_H of hip joint are 0.95 and 0.177 [rad], gain and bias of knee joint are 1 and 0.05 [rad], gain and bias of ankle joint are 1 and 0.256 [rad], gain g_e and variable S of external feedback signal are fixed as 0 for open-loop control, respectively. As a result, it realized the gait of more than 20 steps.

B. Application to Experimental System of Walking Robot

In order to investigate the stable region of the biped walking robot, the open-loop control method used in calculation was tested in the experimental environment. The parameters were tuned by trial and error method. Here, unlike the calculation, gait timing was tuned by swapping the output signal from the learned signal from $State_2$ and $State_3$ to ankle joint and knee joint respectively. The parameters were set as follows; gain g_{AH} and bias B_H of hip joint are 0.95 and 0.007 [rad], gain and bias of knee joint are 1 and 0.2 [rad], gain and bias of ankle joint are 1 and 0.27 [rad], gain g_e and variable S of external feedback signal are both fixed as 0, respectively.

C. Implementation of Feedback Signals

Two types of CPG control with feedback signal, namely, CPG using only posture angle feedback signal and CPG using both posture angle and foot force feedback signals, were tested in the experimental works.

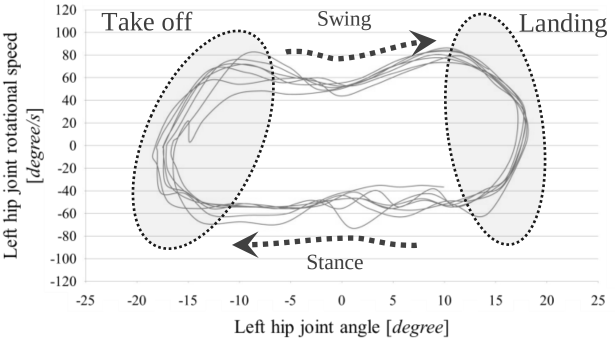

Fig. 9 Phase plot of left hip-joint motion of the 7-linked robot using open-loop type adaptive CPG

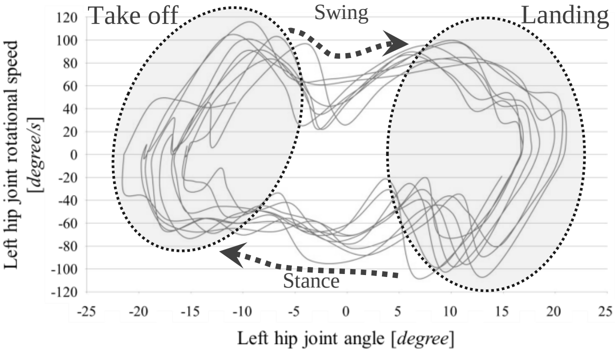

Fig. 10 Phase plot of left hip-joint motion of the 7-linked robot using adaptive CPG with feedbacks

Firstly, walking experiment using the control method with only posture angle feedback signal was tested. Parameters were set as follows; external feedback signal’s gain g_e is 1 and variable S is fixed as 0. Other parameters were set to the same values as in the open-loop control case.

Secondly, walking experiment using the control method with both posture angle and foot force feedback signals was tested. Parameters were set as follows; gain g_{AH} and bias B_H of hip joint are 0.95 and 0 [rad], external feedback signal gain g_e is 1, and variable S is set as binary variable, respectively. Other parameters were set to the same values of open-loop control case.

D. Experimental Results

Three types of walking experiments were carried out. In first experiment, the open-loop CPG control was applied to the robot. Resultantly, it was observed that the robot is capable of performing successful gait motion up to 13 steps at maximum. So it was confirmed that the 7-linked biped walking robot can demonstrate fairly walking motion even only with open-loop controller repeating the learned signals. Secondly, the CPG controller with posture angle feedback signal was applied to the robot, then the resultant number of walking step in its successful case was 2 more steps than that of open-loop. Thirdly, CPG control with posture angle and foot force feedback signals was applied. It was observed that it shows better performance than two other cases and its maximum number of walking step was 17 steps.

The resultant walking motion using both feedback signals is depicted in Fig. 8. The resultant phase plot of the left hip joint using open-loop control CPG is displayed in Fig. 9, also, that of the left hip joint using CPG with feedback signals is displayed in Fig. 10.

According to the graph, it is observed that the shape of phase plot of open-loop control is close to an elliptical shape, which means it is operated according to only the learned signals. In contrast, it was observed that by using the CPG with feedback signals, the phase plot was greatly changed for each step, that means CPG flexibly changes its motion in order to adapt to the external inputs, thus various wave forms were obtained resultantly. Moreover, focusing on motion of the landing and taking off, it was observed that the controller makes the robot to keep its balance by remaining the foot stays on the ground.

In addition, comparison of changes of the upper body posture angle during two walking experiments was carried out. Average value from 3 seconds to 9 seconds after starting walking motion was investigated because, the locomotion gets stabilized after about 2 seconds. It was confirmed that the upper body motion is stabilized by control with the feedback as a result. Where, the change of upper body posture angle was 12.156 [rad] in the case of open-loop control, while that of control with both feedbacks was 11.562 [rad].

V. CONCLUSIONS

An adaptive CPG controller using Hopf oscillator which is capable of generating human-like locomotion was constructed in this research. New teaching signals were designed and tested on computational bipedal models and the experimental bipedal robot. Also, state feedbacks of upper body posture angle and foot force information were implemented for stabilizing the locomotion. From comparing the number of walking steps and the average value of the upper body posture angle, it was confirmed that the proposed control method with the designed teaching signal is effective on generating and stabilizing the locomotion of the 7-linked biped walking robot. Furthermore, from the phase plot of the left hip joint during the walking experiment, it was confirmed that the motion of maintaining the feet on the ground during landing and takeoff motion is an effective element for stabilizing the walking motion.

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