Moving Control of Quadruped Hopping Robot Using Adaptive CPG Networks

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***Abstract*—This paper describes the moving control using the adaptive Central Pattern Generators (CPGs) including motor dynamic models for our developed quadruped hopping robot. The CPGs of each leg is interconnected with each other and by setting their coupling parameters can act as the flexible oscillators of each leg and adjust the hopping height of each leg to require stable hopping motion. The formation of the CPG networks are suitable not only to generate the continuous jumping motion but also can generate the moving motion in two-dimensional, respectively. We also propose the reference height control system which including the maximum hopping height detector and Proportional Integral (PI) controller to achieve the reference jumping height. By using the proposed method, the hopping height of each leg can be control independently in order to make the posture of robot's body incline ahead and move forward. We create MATLAB/Simulink model to conduct various types of experiments and confirmed the effectiveness of our proposed CPG model including the reference height control system to generate the stable moving performance while jumping continuously.**

***Index Terms*—Quadruped hopping robot, CPG networks, Two-dimensional moving control**

I. INTRODUCTION

In half of century, there are a lot of types of autonomous locomotion robot which have been studied and developed. Most of mobile robots are wheeled type locomotion because of the simplicity in robot construction. The wheeled type locomotion excels on prepared surface such as rails and roads, but most of them have not yet been explored. As a result, the study on animal-like robot locomotion i.e. in multi legged, snake-like, bipedal walking and hopping robot has been received much attention from many researchers because of the adaptive locomotion on unknown surface which are frequently faced by mobile robots in real-life environment. Only about half of earth's surface is accessible for wheeled type locomotion and much larger surface can be reached by animal-like locomotion.

The construction of useful legged type locomotion need the systems that able to control joint motion, cycle use of legs, monitor and manipulate balance, generate motions to use known footholds, sense the terrain to find good footholds and calculate negotiable footholds sequences[1]. Perhaps, the most familiar scenario is the sight of a baby advancing rapidly from creeping and crawling to walking, running, hopping, jumping and climbing. Animals also demonstrate great mobility and agility. They move through various environments quickly and reliably. Sometimes, they move with a great speed, often with great efficiency. However, from almost of legged type robots which have been developed are having low energy efficiency and low transferring efficiency while moving performances because of their difficulties on mechanism and control systems.

Consequently, the study on jumping type robot was carried out although it has complex control system. The jumping type locomotion can be divided into two types which are hopping and jumping type robot. The big difference of hopping and jumping type robot is the jumping type robot can make only one big jump moving performance. On the other hand, the hopping type robot can generate the continuous and rhythmical jumping performance while making movement[2]. M.H Raibert is the main contributor of hopping robot which is researched on one-legged hopping robot[1]. The one-legged robot consists of two main parts which are body and leg whereby it equipped with a pair of pneumatic actuators to exert a torque between the leg and the body about to hip. Afterward, Koditscheck and Buhler have created the discrete dynamic system theory to analyze the dynamics of a simplified hopping robot that studied only the vertical movement[3].

Besides, I. Murakami et al. has done his research on hopping robot which control the hopping and moving motion by using the linear DC motor and the gyroscope for attitude control. The linear DC motor was designed into the body part and the leg part of the hopping robot and constructed the direct-drive hopping mechanism[4]. In addition, Okubo et al. has introduced the design of jumping machine using self-energizing spring. His research has produced a machine or robot which can achieve high jumping performance by using small output actuators[5]. Moreover, Tukagoshi et al. has studied on numerical analysis and design for higher jumping rescue robot by using a pneumatic cylinder. They had developed the leg in rotor type robot which can use in flatted smooth surface (wheeled locomotion) and overcome the irregular surface (jumping locomotion)[6]. Meanwhile, Kondo et al. has developed the quadruped hopping robot which is using central pattern generators (CPGs) to generate the continuous jumping performance while control the stability of body balance [7].

Physiological experiments suggest that basic locomotors patterns of most living bodies such as walking, flapping,

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flying and swimming are generated by CPGs which generates rhythmic activities[8]. CPG is neural networks that can endogenously (i.e. without rhythmic sensory or central input) produce rhythmic patterned outputs; these networks underlie the production of most rhythmic motor patterns. The periodic activities of the CPG which are initiated by a burst from the higher motor center induce the muscle activities. After the initiation of the locomotion, the activities of the CPG is affected by sensory signals which show the bending of the body and so on[9]. The procreative sensory feedback plays an important role in the shaping and coordination of the neural activity with the mechanical activity.

Furthermore, neurophysiologic studies of insect locomotion suggest that sensory feedback is involved in patterning motor activity and that it is more than the modulation of the centrally generated pattern[10]. Several researchers are coupled the neuronal circuits to mechanical body and as application of the CPG, a method of designing control systems for legged robot motion has been carried out. On the basic of the definition, walking is locomotion emerging from that interaction between the environment and the body. The first modern evidence that rhythmic motor patterns are centrally generated was the demonstration that the locust nervous system, when isolated from the animal, could produce rhythmic output resembling that observed during flight[11].

Here, Taga proposed a walking motion control mode in which neural oscillator interact with the sensory feedback signals from the musculoskeletal systems[12], [13]. Then, by using the concept of walking motion control model suggested by Taga, Kimura proposed a method of structuring the coupling of neural and mechanical systems for the implementation of autonomous adaption through the irregular terrain[14]. Son et al. proposed a CPG model including the motor dynamic characteristics of an actuator for the purpose of implementing generation adaptive gait patterns for a quadruped robot under various environment[15].

In this paper, we describe the generation of moving control by using the adaptive Central Pattern Generators (CPGs) including motor dynamic models for our developed quadruped hopping robot while jumping continuously. We have approached a new CPG model which is the inhibitory neuron has been replaced with the mechanical dynamic of quadruped hopping robot including the actuator dynamics. By applying the mechanical dynamics of each leg into the CPG model, flexible periodic oscillation can be obtained because the motion feedback loop for the actuator is incorporated into the CPG. Therefore, the adaptive hopping motion can be generated in various environments. On the other hand, the excitatory neuron of the proposed CPGs is mutually connected by the coupling parameters that can adjust the relative phase delay on each leg's locomotion.

Moreover, we propose the collaboration of CPG networks with the feedback control system which are composed the maximum hopping height detector and the Proportional Integral (PI) controller into our developed control system. By adding the feedback loop through the feedback controller, our developed quadruped hopping robot not only can generate the continuous hopping performances but also can control the desired hopping height. Furthermore, we used the reference height control system to give the difference of reference height for each leg of quadruped hopping robot independently. By using the mentioned method, the posture of quadruped hopping robot will incline ahead to the direction which it will move. On the other hand, we evaluated the effectiveness of Central Pattern Generator (CPG) network to keep the stability of quadruped hopping robot and avoiding it from tumble while moving ahead.

A. Robot Construction

Figure 1 shows the construction of our developed quadruped hopping robot (overall length is 49cm, overall width is 49cm, overall height is 37cm and the total weight is 9.1kg). The quadruped hopping robot consists of four legs. Each leg is composed with a DC geared motor (12V, 200min^{-1}, 0.0098 Nm), a crank and a spring which are attached to the crankshaft. Then, each leg is connected to the shared platform.

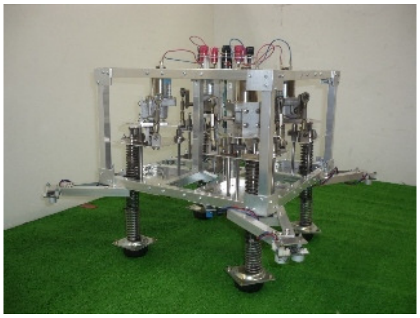


Fig. 1. Developed quadruped hopping robot

The developed quadruped hopping robot is developed with the DC geared motor which is driven by using the DC amplifier and connected to the crank which is used to push the spring under the platform. The hopping motion mechanism of the quadruped hopping robot can be achieve respectively as shown in Fig.2. Here, the motor torque is converted to conserve the energy in the spring and make a periodical jumping motion of hopping robot as the basic of the principle hopping motion. The continuous hopping for quadruped hopping robot can be generated by applying the floor repulsive force when the suitable force was applied to the spring at the suitable time.

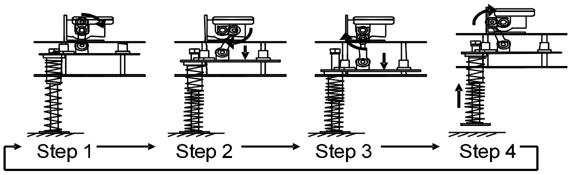


Fig. 2. Principle of hopping mechanism

B. Experimental Setup

Figure 3 shows the experimental setup to evaluate the developed quadruped hopping robot. The proposed CPG network is expressed using a MATLAB/Simulink model on the Host computer. Then the model which is built by the Realtime Workshop is downloaded to the xPC Target computer. The xPC Target computer is run by using a Realtime OS. The jumping position of the center and each leg are measured via the ultrasonic sensors which are used as sensory feedback signals of the CPG. We also included the current sensors into the system which are used to monitor the current value which have given to each leg for each jumping motion. In this experiment, the sampling time for the control is set to 0.01 sec.

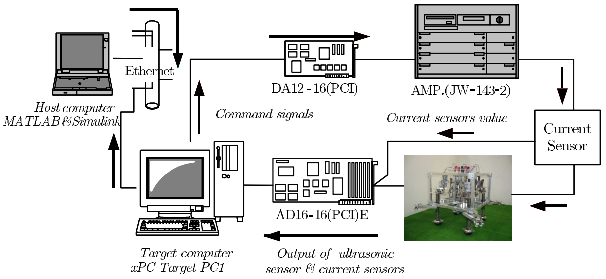


Fig. 3. Experimental setup

II. CONTROL SYSTEM CONFIGURATION

A. CPG model

It has been identified that the CPG plays important roles such as generator of various periodic motions in vertebrate animals. The fundamental CPG model can be expressed as a neural oscillator model that is mutually coupled between excitatory and inhibitory neurons. Figure 4 shows the block diagram of the CPG model which we used as the control system. Here, the inhibitory neuron of the CPG is replaced with the mechanical dynamics for quadruped hopping robot on each leg. The parameters u_e and u_i denote the internal states of the excitatory unit and the inhibitory unit, b and c denote the intrinsic excitatory and inhibitory coupling parameters, a denotes the excitatory coupling factor while B_0 denotes the constant bias input. The output of the inhibitory unit corresponds to the platform position of each leg and is applied to the excitatory unit through a nonlinear function $\tan^{-1}(u_i)$ and the feedback gain b which formulated as

$$\tau_e \frac{du_e}{dt} = -u_e + a\tan^{-1}(u_e) - b\tan^{-1}(u_i) - B_0$$

$$u_i = f(K_a c\tan^{-1}(u_e) - d)$$

where $f(*)$ is the mechanical dynamics of the hopping robot's leg, K_a is the gain constant of the DC amplifier and d is the external disturbance which is the floor repulsive force in this case. By arbitrarily hanging the coupling parameters a, b, c, the time constant τ_e and the mechanical dynamics of the hopping robot, the CPG can change the amplitude and the frequency of internal states u_e and u_i.

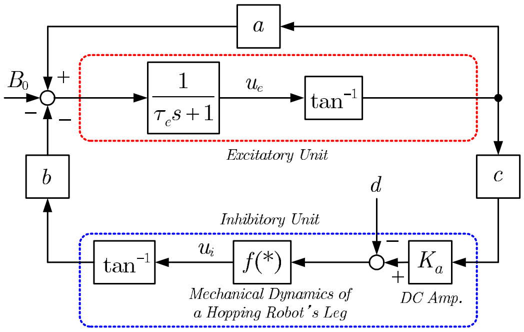


Fig. 4. Block diagram of CPG model

B. Reference height control system

The architecture of the reference height control system for a leg is shown in Fig.5. The proposed control system is composed with the maximum height detector, the PI controller and the CPG. By adding a feedback loop through a fixed gain PI controller, quadruped hopping robot can keep the hopping motion and control the hopping height to achieve the reference hopping height. The control system drives the joint actuator of leg in order to realize the desired hopping position generated by the PI controller, respectively. The PI feedback controller receives the steady-state error which is obtained by deduction of the target hopping position as a reference height h_{ref} and the sensory feedback signals h_{max} from the ultrasonic sensors on each legs.

In control engineering, a PI controller calculates a steady-state error value h_{diff} as the difference between a measured process variable u_i and a reference hopping height h_{ref}. The controller attempts to minimize the error h_{diff} by adjusting the process control inputs. The PI parameters used in the calculation must be tuned according to the nature of the system. The integral term in a PI controller causes the steady-state error adjusted to be zero for a step input. Moreover, we are tuned the PI parameters manually according to the method of threshold sensitivity while the developed hopping robot are jumping continuously. A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive (or sensitive) controller. If the proportional gain is too low, the control action too small when responding to system disturbances.

C. CPG Networks

The quadruped hopping robot is able to jump continuously by applying the same periodic force to each spring of robot's leg and the cooperative oscillation among the CPGs is required. Figures 6(a) and 6(b) show the configuration of typical CPG

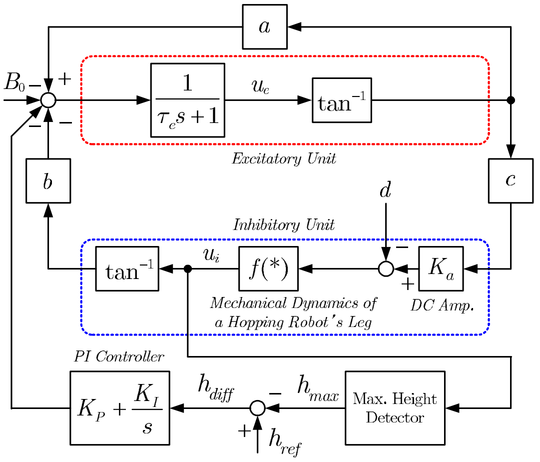
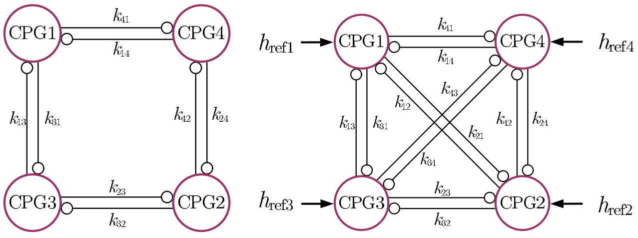


Fig. 5. Block diagram of reference height control system

networks. By using this ring-and-cross type CPG networks, we can obtained the stable, continuous and rhythmical hopping performances[7]. In addition, we included the reference height control system with CPG model into each of robot's leg. Therefore, the hopping height of each leg can be controlled independently according to the reference height which has been set. The structure of CPG networks used in this paper is illustrated in Fig.6(b).



(a) Ring type (b) Ring-and-cross type

Fig. 6. Configuration of typical CPG networks

III. EXPERIMENTAL RESULTS

A. *Evaluation of CPG Networks*

In order to confirm the effectiveness of our proposed CPG networks and the reference height control system, we have conducted three types of experiments. Firstly, we have conducted the experiment of our developed quadruped hopping robot including our proposed CPG networks on the irregular terrain. As for comparing with it, we also conducted the experiment without using CPG networks. The condition of this experiment for instance the leg 2 and leg 3 are set on the low level, whereas; leg 1 and leg 4 are set on the high level can be illustrated in Fig.7. The differences between the high level and low level are about 3cm.

As the results, Fig.8 shows the experimental results by using CPG networks on flat floor. The highest position at each jump converges to a constant value of 20cm after transient state 0.8 sec. Then, we are obtained the experimental results of jumping height for each leg and the center position of shared platform by not using the CPG networks in Fig.9. In this case, we only give a constant voltage 6V (absolute value) as the control signals to drive the DC geared motor. Here, we could know that the body of the quadruped hopping robot while not using CPG network are tumbled after having unstable hopping motion. On the other hand, Figure 10 shows the jumping height of each leg and the center position of the shared platform by using the CPG networks on irregular terrain. Hence, the CPG network coupling parameters which we proposed is $a = 0.1$, $b = 5$, $c = 1$, and $B_0 = 0.01$ $\tau_e = 0.1$. From the results, we could know that the body of quadruped hopping robot by using the CPG network are stable and not tumble in whole experimental time, although it shakes vigorously.

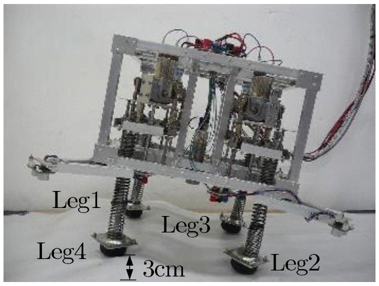


Fig. 7. Experimental condition

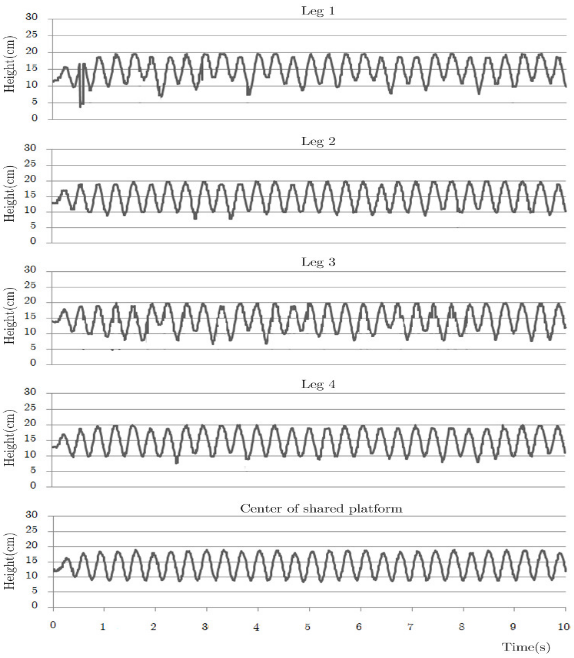


Fig. 8. Hopping motion with ring-cross type CPG networks on regular terrain

B. *Evaluation of Reference Height Control System*

Furthermore, we also conducted the experiment to confirm the validity of our proposed reference height control system.

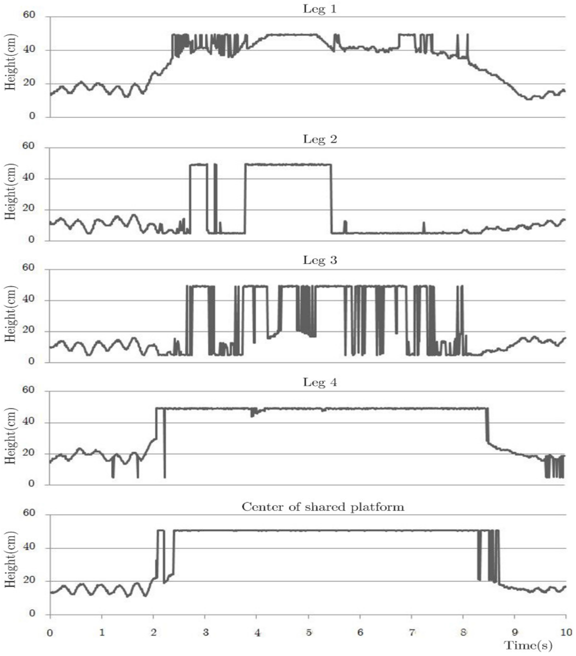


Fig. 9. Hopping motion without ring type CPG networks on irregular terrain

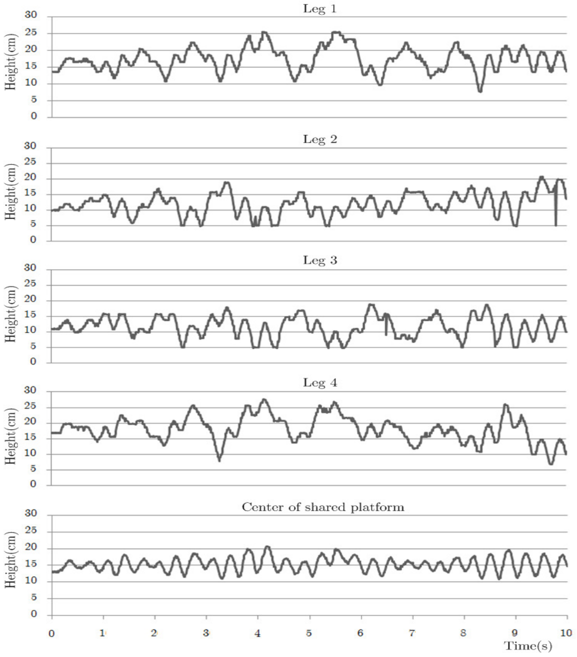


Fig. 10. Hopping motion with ring-cross type CPG networks on irregular terrain

Firstly, this experiment was conducted to evaluate the effectiveness by using P controller only to achieve the reference hopping height. The experimental results by using only P controller are shown in Fig.11. These figures show the jumping height, command signal, difference, feedback signal and center jumping height of shared platform for leg1 only because the experimental results of other legs are similar to the leg1's results. In the figure of jumping height, difference between the reference height and measured height and center jumping height, the vertical axe indicates the height (cm) and horizontal axe indicates the time (sec). But for the command signal and feedback signal the vertical axe indicates the voltage (V) and horizontal axes indicate the time (sec). Here, the figure for command signal shows the voltage which having an absolute value. In these figures, we set the position of ultrasonic sensors at 13cm as the initial position start from 0 and the oscillation of the spring which is shown as plus and minus means the spring are stretching or compressing. And we did the whole experiment in 30sec to evaluate the stability of our proposed PI controller system.

In this experiment, the reference hopping height which is set to each leg is 5cm. The CPG parameters and the CPG network coupling parameters are set as $a = 0.1$, $b = 5$, $c = 1$, $B_0 = 0.01$, $\tau_e = 0.1$, $f = 0.1$. Moreover, the P controller's gain is set as $K_P = 5.5$ according to the result of tuning by threshold sensitivity method. From the experimental results, we can see the hopping height which we obtained is approximately 6cm and the difference is approximately 1cm. From these experimental results, we know that the difference (steady-state error) cannot converge to zero and the target hopping height cannot be achieved by using only P controller. In control engineering, a PI controller is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between the ultrasonic sensor output and reference hopping height) and the integral of that value. The integral term in a PI controller causes the steady-state error to be zero as the feedback control signal.

Therefore, we are designed the new control system by using PI controller to compare with the system of P controller and converge the steady state error which are obtained in previous experiment to zero. The experiment using PI controller was carried out in order to evaluate the effectiveness of new PI controller. In this case, the reference hopping position, CPG parameters and CPG network coupling parameters are same with the previous experiment by applying the P and I gain as $K_P = 5.5$ and $K_I = 0.4$. Here, I gain is the best value which we also tuned by threshold sensitivity method. The experimental results for PI controller are shown in Fig.12. These figures are included the jumping height, command signal, difference, feedback signal and center jumping height for one leg which is CPG1 from our developed quadruped hopping robot. From the experimental results of PI controller, we confirmed the effectiveness of PI controller to converge the steady state error to zero. The reference hopping height of our developed quadruped hopping robot is achieved at 21sec after the steady-state error tried to converge to zero from 5sec to 20sec.

Here, the whole systems of PI controller causes the steady-state error (difference between the ultrasonic sensor output and reference hopping height) converge to zero which could be seen from the figure of difference in Fig.12. And the command signal that given to the each DC geared motor is adjusted with the feedback signal which obtained from the PI controller. We also can know that the sensory feedback from the ultrasonic sensors measures the current maximum hopping height and if the desired hopping positions are not achieved; more voltage will be supplied as the input voltage to generate higher hopping position by the DC geared motor. In contrast, when the current hopping height are over than reference hopping height, less voltage will be supplied to the DC geared motor to generate the stable hopping performance. Therefore, by using PI controller we confirmed that the steady-state errors of hopping height converge to zero at last. And we also confirmed the effectiveness of proposed control system with the CPG network could make the stable hopping performances which is shown at the figure of center height in Fig.12.

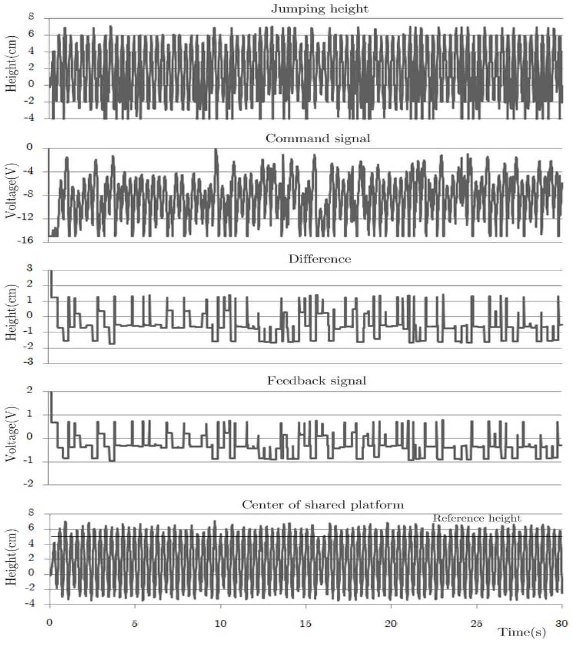


Fig. 11. Experimental results of reference height control sytem using only P controller

C. Evaluation of Moving Motion

After we confirmed the effectiveness of our developed reference height control system, we are conducted the experiment of moving performance on two-dimensional level surface. Here, the internal parameters of CPGs are set to the typical value as $a = 0.1$, $b = 2$, $c = 1$, $B_0 = 0.01$, $\tau_e = 0.1$, $f = 0.1$ and the PI controller's gains are set as $K_P = 5.5$ and $K_I = 0.4$ in advance, in order to generate the efficient hopping motion. In this experiment, we are applied the reference height control system to control the reference hopping height for each leg of our developed quadruped hopping robot. We are conducted the whole experiment in 50sec which in the first 5sec period, we set the reference hopping height for all legs to 20cm in order to maintain the oscillation of hopping performances, at first. Then, as well as our developed quadruped hopping robot leg's position are shown in Fig.6, we set the reference height for leg 1 and leg 3 (assume as front of body) to 18cm and leg 2 and leg 4(assume as rear of body) to 20cm in order to make the posture of hopping robot's body incline ahead to the direction which it should be move forward.

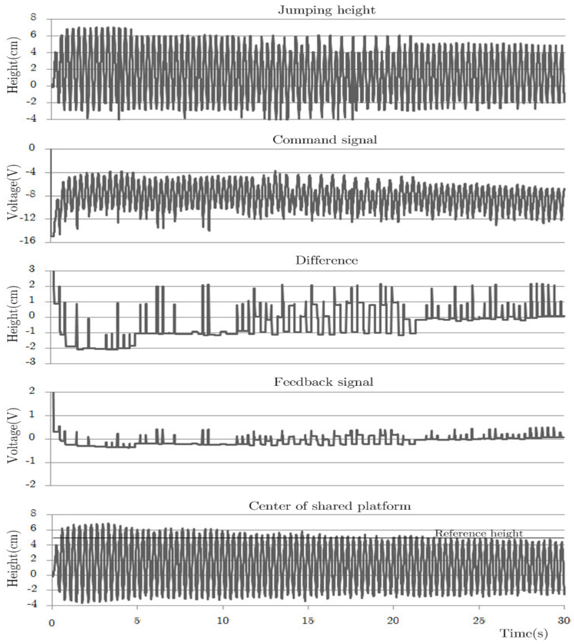


Fig. 12. Experimental results of reference height control sytem using PI controller

The experimental results for our proposed moving method can be illustrated in Fig.13. These experimental results are including 4 types of output signals such as the maximum hopping height value h_{max} on each jump which are scraped by using the ultrasonic sensors for each leg. Then, the signal of differences (steady state error) h_{diff} which are obtained from comparing the reference height h_{ref} with the maximum hopping height value h_{max} and the command signals which have been sent from DC amplifier to the DC geared motor of quadruped hopping robot. And the last output signal is the current sensors values which are measured by using the current sensors which we mounted on each DC geared motor of each leg. In Fig.13, the output signals of current sensors values and command signals are shown at the top of the figure following with the output signals of differences (steady state error) and maximum hopping height value at the second graph. Both graphs are illustrated for leg 1 and followed with the graph of other's leg. For the current sensors values and command signals graph, we are using the primary y-axis for current sensors value which the unit is Ampere (A) and the command signals are using the secondary y-axis which unit is Voltage (V). The figures for the command signals, the power voltage can be thought as the absolute value.

From these experimental results, we can see that our quadruped hopping robot are succeed to attain the reference hopping height of all legs which are set to 20cm at the first 5sec period while hopping in one-dimensional level. Then after 5sec, we could see the changing of command signals and the

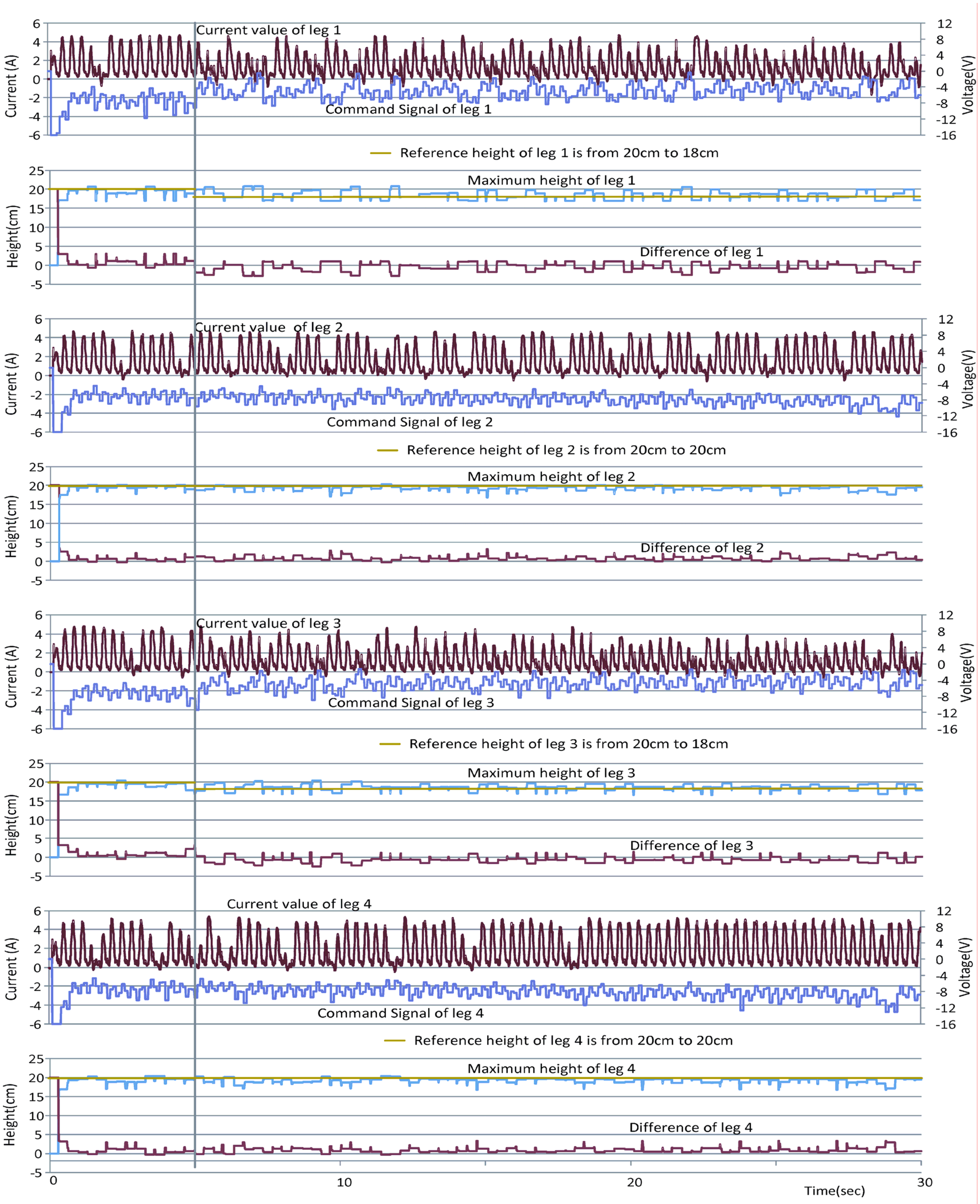


Fig. 13. Experimental results for moving performances in 30sec

current sensors value in order to implement the moving performances following by the changing of reference height on each leg. Here, we could know that the leg 1 and leg 3 are trying to achieve the reference height which is set to 18cm by decreasing the power voltage value about 50% and oscillated around -4V to -8V which are supplied to the DC motor. On the other side, the power voltage value for leg 2 and leg 4 are maintained same as the first 5sec period level in order to maintain the reference height at 20cm. At the same time, the current sensors value for leg 1 and leg 3 are decreasing cause the load value while the command signals are decreased. Meanwhile, the current sensors value for leg 2 and leg 4 are same at the whole experiment although sometimes the current sensors values are little bit decreased periodically. The changing of current sensors value periodically was because the leg 1 and leg 3 are increased their power voltage. Therefore, the power voltage for leg 2 and leg 4 are decreasing to keep the balancing of quadruped hopping robot's body. Here, we confirmed the validity of CPG networks system which is functioned to maintain the stability of quadruped hopping robot and avoiding it from tumble ahead.

From the result of controlling the command signals, the differences (steady state error) have been obtained from each leg are entered the PI controller system to converge the differences to be zero. Therefore, the maximum hopping height can be achieved according to the reference height which has been set. Especially, the differences for leg 1 and leg 3 are tried to converge to zero that we can see from the figure that the differences are stayed around 1cm compared to the reference height. Besides, the differences for leg 2 and leg 4 are converged to zero and successful to keep the maximum hopping height at 20cm in the whole experiment. In addition, the moving distance which has been succeeded is 120cm in 50sec experimental time.

IV. CONCLUSION

In this paper, the application of CPG networks for quadruped hopping robot has been described. We are included the actuators in mechanical dynamics hopping robot which is mounted on each leg and coupled with each other as the CPG networks. By combining the CPG network of each leg, we obtained successful and stable hopping performances on irregular terrain compared with the hopping motion without CPG networks. Consequently, the quadruped hopping robot are tried to give the stabilization to the whole hopping robot body from tumble by cooperating with other legs by using CPG networks, although it shakes vigorously. On the other hand, we evaluated the CPG networks which act as a command centre for the musculoskeletal system. Moreover, we confirmed the effectiveness of our proposed reference height control systems to generate the continuous hopping performances and to control the reference hopping height of our developed quadruped hopping robot. By using the collaboration of CPG networks and the PI feedback controller, we obtained the successful hopping performance while the hopping height of the quadruped hopping robot achieved the reference hopping position.

Furthermore, we have proposed the moving method which we applied the effectiveness of reference height control system to conduct the reference hopping height on each jumping period independently. By setting the different reference hopping height on each leg of quadruped hopping robot, the posture of robot's body could inclined forward to the direction which it should move. As the results, we confirmed the successful moving performances while hopping continuously and rhythmically in two-dimensional level surface. In addition, we also obtained the effectiveness of CPG networks which act as a command centre for the musculoskeletal system to generate the continuous hopping performances and to keep the stability of quadruped hopping robot and avoiding it from tumble ahead.

In the future, we aim to investigate various types of moving motion for our developed quadruped hopping robot. Besides, we also aim to develop the learning algorithm to acquire the CPG parameters and coupling parameters of CPG networks automatically for hopping on an arbitrary place. On the other hand, we would like to tune the PI controller's gain by online tuning method.

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