

Stable Quadruped Walking with the Adjustment of the Center of Gravity

Xian Wu, Xuesong Shao, Wei Wang

Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China

xianwucas@gmail.com, xuesong.shao@gmail.com, wei.wang@ia.ac.cn

Abstract - The quadruped robot excels in tight space traversing and rough terrain locomotion because of its higher flexibility and better environment adaptability. Aiming at passing through tight spaces with free-collision, an adjustment approach of the Center of Gravity (COG) is designed to realize stable quadruped walking. The Hopf oscillator based Central Pattern Generator (CPG), utilized in this paper, can generate rhythmic control signals with different frequencies for the swing phase and the stance phase. The COG is adjusted through the rhythmic medium value transition, which automatically generates smooth trajectories according to preset parameters. We also propose a rhythmic bias compensation method to maintain the rhythmic medium positions of legs vertical to the ground to alleviate the bump caused by the body pitch. Still, an adjustment technique for the hip motion amplitude is developed to maintain the uniform motion when the robot posture changes. We evaluate the performance of the COG adjustment approach on a simulated quadruped robot model, and the simulation of the tight space negotiating of the robot model demonstrates the stable quadruped locomotion.

Index Terms - quadruped robot; central pattern generator; center of gravity; adjustment.

I. INTRODUCTION

The quadruped robot with prominent maneuverability and environment adaptability excels in traversing rough terrains. Thus, one promising perspective of the robot is to implement high risk tasks, such as rescue and carriage particularly in environments which are hard to access for humans. The performance of legged locomotion decides whether the quadruped robot can be put into practical use. There is a lot of work about investigating quadruped locomotion in rocky and sloped terrains, but solutions for tight space traversing are rare. The quadruped robot for Fukushima Nuclear Power Plant, developed by Toshiba Corporation, is designed to implement investigative and recovery work in hard-to-access locations. The robot can squeeze in tight spaces by separating a smaller companion robot [1]. However, this does not meet the need that traverses tight spaces by itself.

Researchers have proposed a large amount of approaches for adaptive locomotion. Many previous investigations are evocative and inspiring, such as Cheetah, Bigdog and LS3 [2, 3, 4]. However, no technical details about locomotion have been published. Kolter et al. present a hierarchical control architecture that enables the quadruped robot to walk through rough terrain. The method makes use of a fully terrain map relying on stereo vision and learning techniques [5, 6]. Another vein of enhancing adaptability is by modifying mathematical model that began by Righetti and Ijspeert. They

add the sensory feedback in locomotion generation model such that the model is strongly coupled with the mechanical system it controls [7, 8]. Therefore, the presented robot can implement task with desired trajectory. Besides, special mechanical systems are also efficient to enhance the robustness locomotion over rough terrains. For example, the quadruped robot Tekken, used passive ankle joints with lock and spring mechanism, is capable to walk on irregular terrains [9].

The CPG, inspired by animal rhythmic locomotion, is a main approach for legged movement. The humanoid robot iCub combines rhythmic and discrete motion to turn, drum, reach and crawl [8]. The quadruped robot HyQ utilizes a reactive controller framework to traverse irregular terrain stably [10]. Besides, the self-reconfigurable robot UBot is capable to implement quadruped walking and snake-type wiggling [11]. These robots achieve impressive locomotion, but the walking with the adjustment of the COG is rarely proposed.

The quadruped robot FROG (Four-legged Robot for Optimal Gaits), built in our lab and shown in Fig. 1, is motivated by the desire to work in places where the environment is dangerous for humans. The remote-controlled robot is attached with a stereo vision camera mounted on the pan/tilt platform [12]. The robot has already achieved obstacle striding by trajectory planning and posture adjustment [13], adaptive walking on different ground substrates through interaction dynamics [14], and locomotion in unknown environments with stereo vision [15].



Fig. 1 The quadruped robot FROG, created at our lab.

The purpose of this paper is to propose a COG adjustment approach for the quadruped robot traversing tight spaces which inevitably exist in unstructured environments. We utilize the Hopf oscillator based CPG to generate rhythmic control signals with different frequencies for the swing phase and the stance phase, so that gaits and speed are controllable. The center of

gravity is adjusted through the rhythmic medium value transition, which automatically generates smooth trajectory according to preset parameters. The rhythmic bias compensation method is proposed to alleviate severe bumps caused by pitching of the quadruped robot. Besides, the speed of locomotion is not affected by the robot pitch with the hip motion amplitude adjustment technique.

The rest of this paper is organized as follows. We present the CPG model with the adjustable phase in section II. After that, we introduce the adjustment strategy of the center of gravity in details in section III. Section IV shows the results of experiments on a simulated quadruped robot model. Section V concludes this paper and describes the future work.

II. CENTRAL PATTERN GENERATOR WITH THE ADJUSTABLE PHASE

Our approach for generating rhythmic locomotion adopts a CPG model, which is inspired by rhythmic locomotion of animals. Considering smooth gait switching and frequency modifying for the swing phase and the stance phase independently, we utilize the CPG model based on Hopf oscillators [7], to drive joint motion of legs. The CPG model is defined by the following equations:

$$\dot{x}_i = \alpha(\mu_i - r_i^2)x_i - \omega_i z_i, \quad (1)$$

$$\dot{z}_i = \alpha(\mu_i - r_i^2)x_i + \omega_i z_i, \quad (2)$$

$$\omega_i = \frac{\omega_{stance}}{e^{-bz_i} + 1} + \frac{\omega_{swing}}{e^{bz_i} + 1}. \quad (3)$$

where $r_i = \sqrt{x_i^2 + z_i^2}$, i denotes the index of legs, x_i and z_i (when $z_i < 0$) are the i th oscillator outputs. $\sqrt{\mu_i}$ is the oscillation amplitude (when $\mu > 0$), for $\mu < 0$ the output signal amplitudes are equal to zero, the oscillator frequency is ω , which is determined by ω_{stance} and ω_{swing} controlling frequencies of the stance phase and the swing phase respectively, and α adjusts the convergence speed. The oscillation period is $T = \frac{\pi}{\omega_{swing}} + \frac{\pi}{\omega_{stance}}$.

In order to achieve quadruped locomotion, identical oscillators should be connected in proper coupled phase relationship. The phase difference between the oscillator i and the oscillator j can be modulated by extending (1) and (2) [8], shown as follows:

$$\dot{x}_i = \dots + \sum_{j \neq i} K_{ij} (\cos(\theta_{ij})x_j - \sin(\theta_{ij})z_j), \quad (4)$$

$$\dot{z}_i = \dots + \sum_{j \neq i} K_{ij} (\sin(\theta_{ij})x_j + \cos(\theta_{ij})z_j). \quad (5)$$

where θ_{ij} is the relative phase difference between the oscillation i and the oscillation j , fulfilling the periodic stepping sequence. Gait setting and gait transition are possible by setting the value of K_{ij} . K_{ij} is the coupling coefficient, which influences the amplitudes of oscillators. Here, we define k as

the influence factor of the coupled oscillation amplitude. The coupled oscillation amplitude is $k\sqrt{\mu_i}$. k can only be obtained by priori experiments since no formula to figure it out.

III. ADJUSTMENT OF THE CENTER OF GRAVITY

The rhythmic locomotion based on the CPG model allows the quadruped robot to transfer gaits and to regulate movement speed. However, the rhythmic generator itself is unable to modulate the rhythmic medium value, which is crucial for the adjustment of the COG.

In order to achieve stable quadruped locomotion with the adjustment of the COG, we present three sub-modules in the adjustment strategy: rhythmic medium value transition that adjusts motion postures of the quadruped robot; rhythmic bias compensation that alleviates bumps caused by the body pitch; hip motion amplitude adjustment that maintains the uniform motion when the robot posture changes.

A. Rhythmic Medium Value Transition

The combination of the rhythmic locomotion and the rhythmic medium value adjustment enables robots to walk with posture modulation. The combination has been realized by adding discrete motion generator in the CPG model, leading to the coupling of the planning phase and the actual trajectory generation [8]. However, the amplitudes of oscillators change irregularly with coupling offset signals, and the output signals have unexpected phase shift. This combination model is unsuitable to apply in our approach, since accurate control signals are necessary for posture adjustment of the quadruped robot. Thus, we combine the rhythmic locomotion and the rhythmic medium value adjustment by adding posture adjustment trajectory to rhythmic signals.

The posture adjustment requires smooth transition signals for driving joint motion. It is desirable that smooth trajectory is modulated by setting target values. The modulation has been achieved by utilizing Vector Integration to Endpoint (VITE) [16]. However, the model is implicit in transition time, which is necessary for modulating medium value trajectory in time-varying environments. Thus, we modified the VITE model, shown as follows:

$$\ddot{y}_{ix/z} = \frac{T_c^2}{T_{ix/z}^2}(O_{ix/z} - y_{ix/z}) - \frac{2T_c}{T_{ix/z}} \dot{y}_{ix/z}. \quad (6)$$

where $O_{ix/z}$ is the input of target values. $y_{ix/z}$ is the output medium value trajectory with corresponding transition. $T_{ix/z}$ is a constant for controlling the transition time when the value of $O_{ix/z}$ is changed. T_c is a system constant, which should be set according to the magnitude of input values.

To further illustrate the system constant T_c , we compute the solution of (6) to find out the influence. The solution is:

$$y_{ix/z} = O_{ix/z}(1 - e^{-\frac{T_c}{T_{ix/z}}t}) \left(1 + \frac{T_c}{T_{ix/z}}t\right), \quad (7)$$

if the initial value of $y_{ix/z}$ is zero. t is the time variable which begins at the changing of the input value. When $t = T_{ix/z}$, we can get that $y_{ix/z} = O_{ix/z}(1 - e^{T_c}(1+T_c))$. Hence, T_c decides the output proportional value of $O_{ix/z}$ after transition. In our approach, the range of medium value is from $-\pi$ to π . Aiming at outputting the preset value, we set $T_c = 8$ s so that $y_{ix/z} = 0.997O_{ix/z}$.

To make the above rhythmic medium value transition method more intuitive, we present the input and output signals in Fig. 2. The transition time of the output signal is precisely equal to the preset value.

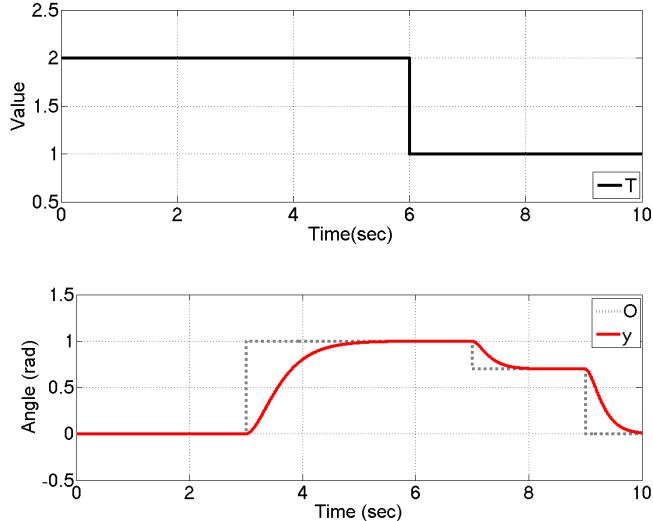


Fig. 2 Top panel: the value of transition time. Bottom panel: O represents the input signal. y is the output signal after transition.

B. Rhythmic Bias Compensation

Based on the rhythmic medium value transition, the COG of the robot can be adjusted by setting parameters. Moreover, combining the medium value transition with the rhythmic motion works well in the locomotion with adjustment of the COG, which is modulated by extending or bending legs in symmetric structure.

Nevertheless, this kind of modulation is not suitable for all situations. Although bending all legs really works, it causes a large amount of energy consumption. In nature, quadruped animals, before traversing a tight space, always bent forelegs to see whether there has a outlet, after that they decide whether pass through or step back. Unfortunately, we found the simulation locomotion with bending forelegs bumps severely. To analyze the bump reason, we depict the diagram of diagonal legs and the foot trajectories in the stance phase, as shown in Fig. 3. In the simulation, we set that the rhythmic medium values of legs maintain perpendicular to the robot trunk in locomotion and the knee joint is fixed in the stance phase. Since the distance from the hip to the foot, in a same leg, is constant in the stance phase, the foot trajectory can be denoted as a circular arc. The radius is the distance from the hip to the foot and the center is the hip joint. The arc along the center rotates θ_{pitch} with the body pitch. We find that the height difference between Anterior Extreme Position (AEP) and Posterior Extreme Position (PEP) becomes bigger as the

increase of the body pitch angle. So bumps are generated when one leg locates in AEP and the other side one simultaneously locates in PEP with different height.

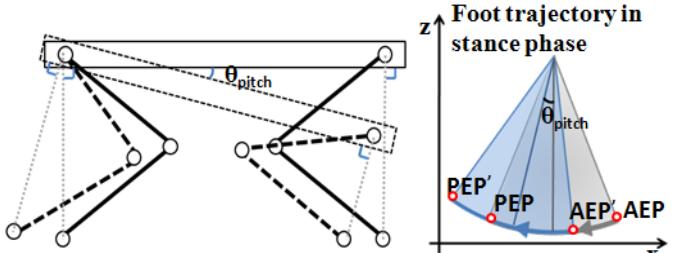


Fig. 3 The pitching diagram of diagonal legs (left) and the foot trajectories of a leg in pitch and normal state during the stance phase (right). The θ_{pitch} is the pitch angle caused by the differential distance between the hip to the foot of the fore leg and the hind leg. AEP and AEP' are the anterior extreme position of the normal and bending legs respectively. PEP and PEP' are the posterior extreme position of the normal and bending leg respectively.

Modulating knee joints to eliminate the height difference between PEP and AEP is achievable by computing the compensation angle in real time. However, the quadruped locomotion without flexed knee joints in the stance phase may lead to the foot slippage. Therefore, we should find another way to alleviate severely bumps. Note that the foot trajectory of the pitch body will overlap to the normal one if the arc along the circle center rotates back about θ_{pitch} . So the difference between AEP and PEP can be eliminated by rhythmic bias compensation, which subtracts the value of real-time feedback pitch angle of the body to the output signals of hip joints. The rhythmic medium values of four legs maintain vertical to ground in locomotion with the bias compensation.

C. Hip Motion Amplitude Adjustment

The rhythmic bias compensation alleviates severe bumps by eliminating the height difference between AEP and PEP. However, the factor that may also causes bumps is omitted. Before illustrating the factor, we define the distance from PEP to AEP of one leg as the leg step length, for distinguishing it from a single step length of the robot. Leg step lengths of four legs with the same hip motion amplitude are difference when the robot posture in locomotion is asymmetric. For example, the leg step length of the bending foreleg is shorter than the one of hind legs in normal state. The difference of leg step lengths, which can cause bumping or even falling over, is undesirable. Therefore, maintaining the leg step lengths of four legs equality is necessary. Besides, locomotion speed should not be affected by the COG modulation

To achieve the desired goals, the hip motion amplitudes should be adjusted to keep four leg step lengths equal to the robot step length before the COG position modulating. Fortunately, the rhythmic bias compensation which maintains the rhythmic medium positions of legs vertical to the ground, makes solution simple and achievable. To keep the motion uniform, we modulate the hip motion amplitude by setting μ_{ic} to replace μ_i in (1) and (2). According to geometrical relationship, μ_{ic} can be formulated as:

$$\mu_{ic} = \left(\arcsin\left(\frac{L_{iorg}}{L_{icur}} \sin \sqrt{\mu_i}\right) \right)^2. \quad (8)$$

where L_{iorg} and L_{icur} denote the distances from the hip to the foot of leg i in initial state and current state respectively. The L_{icur} can be obtained according to y_{ixz} which is the medium value of the hip/knee joint in leg i .

By the hip motion amplitude adjustment equation, μ_{ic} can be obtained automatically. In addition, the leg step lengths of four legs are equal to the value before the COG adjusting. The locomotion speed is not affected by the robot pitch.

IV. SIMULATIONS AND DISCUSSIONS

In this section, we present two experiments to show the locomotion with the adjustment of the COG achieved by the proposed approach. The first experiment presents the performance of the approach and the influence of sub-modules. The second experiment simulates that the quadruped robot negotiates a tight space by making use of the approach.

The simulation experiments are performed on a simulated quadruped robot model in MSC.Adams, a software for simulating 3D rigid body dynamics. The simulated robot, modeled partly according to our quadruped robot FROG, has 12 DOFs, and the hip yaw joints are fixed in our experiments. The robot is 0.632m tall with a total weight of approximately 48kg. The length of thigh and shank are 0.35m and 0.38m respectively, the trunk length is 1.05m, and the width of trunk is 0.72m. We set the initial angle between the trunk and the thigh as $\pi/3$ rad, and the initial angle between the thigh and the shank as $2\pi/3$ rad.

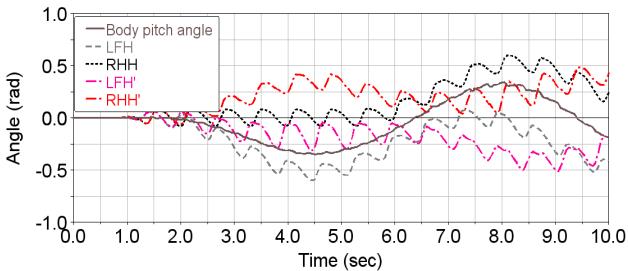


Fig. 4 Output control signals and the body pitch angle. LFH and RHH are signals to control hip joints of left front leg and right hind leg respectively, without rhythmic bias compensating and hip motion amplitude adjusting. LFH' and RHH' represent the control signals with rhythmic bias compensating and amplitude adjusting. Note that the amplitudes of LFH' and RHH' change while modulating the rhythmic medium value.

First, to show the performance of adjustment approach, we set an extreme case that the body pitch angle and the COG position in height change in a large variation. The control signals and body pitch angle are shown in Fig. 4. The negative and positive values of the pitch angle represent pitching down and up. LFH and RHH, generated by the CPG model and the rhythmic medium value transition, show the control trajectories

of hip joints in left front leg and right hind leg. The trajectories of LFH and RHH are modulated in real time by the rhythmic bias compensation and the hip motion amplitude adjustment. The modulated trajectories are LFH' and RHH'.

Furthermore, to analyze the influence of sub-modules, we show the COG trajectories in three control structures, with same parameters in the first experiment. We set the rhythmic medium value transition and the CPG model as the basic control structure, since it can control the basic quadruped walk with the adjustment of the COG. The performances of sub-modules are shown by removing sub-modules of control approach: the basic structure, the basic construct and rhythmic bias compensation, and the complete approach. The COG trajectories of heights and lateral displacements are shown in Fig. 5.

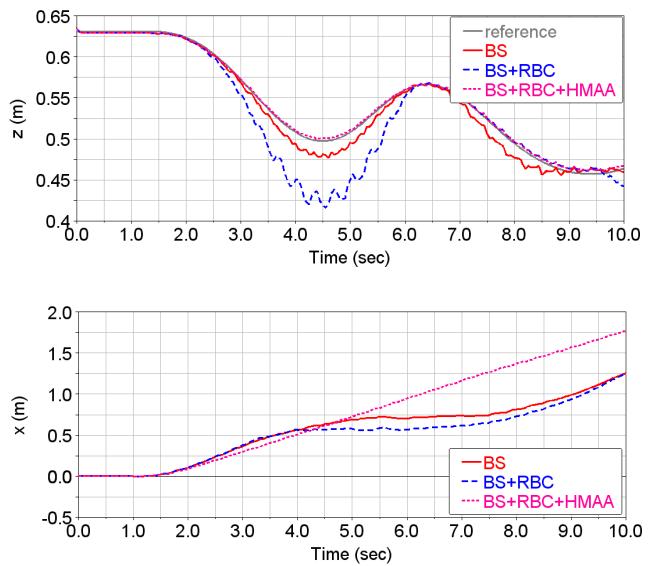


Fig. 5 Experiment results of COG trajectories in strategy performance tests. BS, RBC and HMAA represent the basic structure, the rhythmic bias compensation and the hip motion amplitude adjustment respectively. Three simulation cases are: MT, MT and RBC, and the complete approach. The top and bottom plots show the COG trajectories in x and y directions. The reference curve represents the preset trajectory.

Although the robot body pitches in a large variation, the COG trajectory with the complete approach, still almost overlaps the preset trajectory. Accordingly, the adjustment approach is effective and reliable. In addition, the noteworthy phenomenon in Fig. 5 is that the locomotion with the adjustment of the COG, lacking of the hip motion amplitude adjustment, performs even worse than the locomotion with the basic structure. This phenomenon is caused by the fact that the difference of fore and hind leg step lengths becomes bigger due to keep the rhythmic medium position vertical to ground than one without rhythmic bias compensating.

In the second experiment, the COG adjustment approach is applied on the simulated quadruped robot model to traverse a tight space. The simulation environment is set as follows: the thickness of the wall is 0.2m and the quadruped robot stands 1.3m away from the wall. A rectangle hole with 0.8m wide and

0.4m high is in front of the robot. The overview of the simulation environment is shown in Fig. 6.

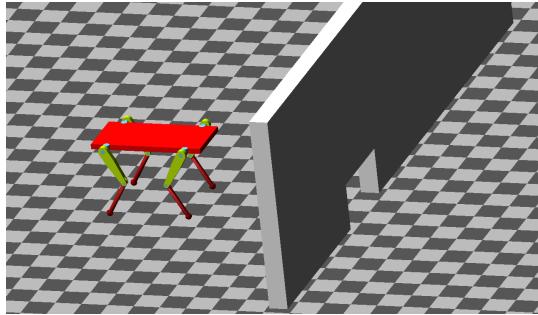


Fig. 6 Overview of the simulation environment.

The whole traversing process can be decomposed into five steps: (1) flexing the front legs to approach the tight passageway; (2) flexing the hind legs to across until the body squeezes in it; (3) crouched moving in the tight space; (4) extending the front legs when the body goes out; (5) extending the hind legs back to the initial state.

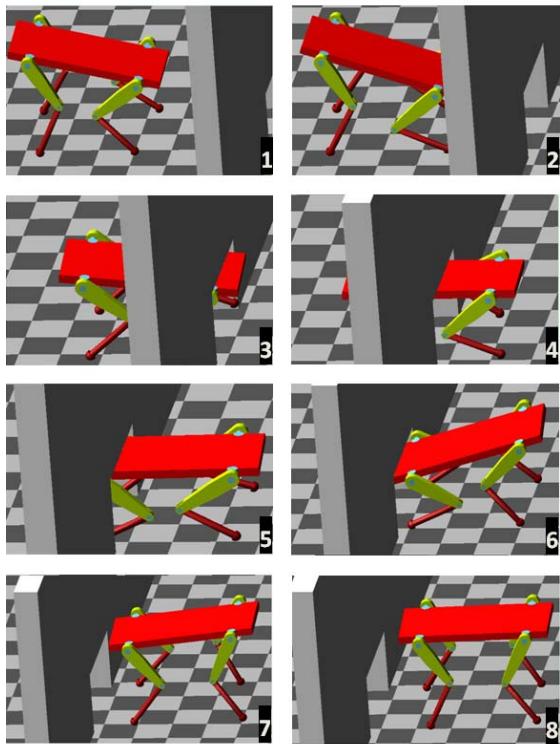


Fig. 7 Snapshots of the simulated model while traversing a hole. Number 1 to 8 denote the moving sequence.

Fig. 7 shows the snapshots of the simulated quadruped robot model while traversing a hole. The front two pictures belong to the first step, number 3 corresponds to the second step, number 4 and 5 present the third step, number 6 and 7 show the step four, and the rest picture depicts the last step.

The output signals and the COG trajectory in lateral plane are shown in Fig. 8 and Fig. 9. In addition, the output signals are the control signals which are modulated by the rhythmic bias compensation and the hip motion amplitude adjustment.

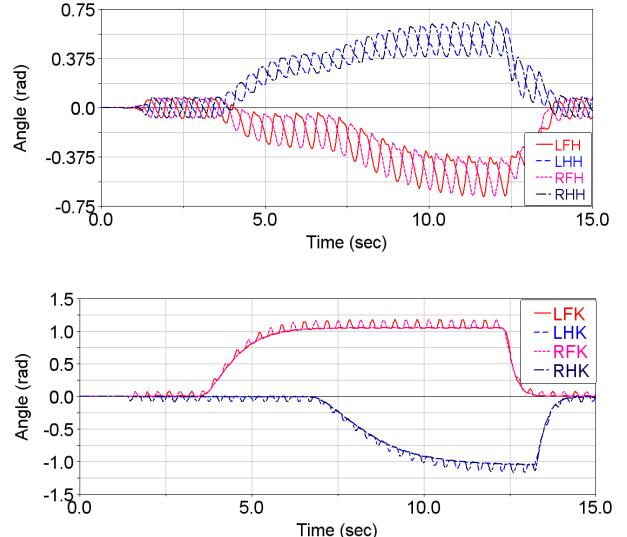


Fig. 8 Output signals of hip joints (top) and knee joints (bottom).

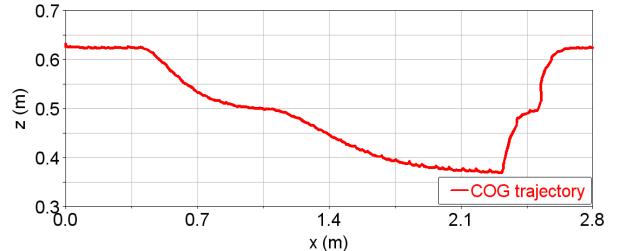


Fig. 9 COG trajectory in lateral plane.

V. CONCLUSIONS AND FUTURE WORK

This paper presents a stable quadruped walking approach with the COG modulation. The key feature is that the approach adjusts output signals of the CPG model according to COG trajectories automatically and smoothly, such that the locomotion with the adjustment of the COG is stable with the pitching body. We choose the CPG model based on coupled Hopf oscillators to generate rhythmic motion for locomotion. We utilize the rhythmic medium value transition to adjust the COG trajectory. The rhythmic bias compensation with the feedback pitch angle alleviates bumps caused by body pitch. The hip motion amplitude adjustment enables the robot to maintain the uniform motion when the leg length changes.

We evaluate the performance of the COG adjustment approach on a simulated quadruped robot model. The experiment results demonstrate the reliability of the adjustment approach.

Future work will be aimed at adding a planning layer for generating the COG trajectory by stereo vision automatically.

Furthermore, the COG adjustment approach with planning layer will be evaluated on our quadruped robot FROG.

ACKNOWLEDGMENT

This work is supported partially by National Natural Science Foundation of China under grants U1201251, and National Science and Technology Support Program of China under grants 2012BAF11B04.

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