Turning methods for quadruped robot with two degrees of freedom per leg

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Abstract: With the target at simplicity like facilitating the mechanical system, the quadruped robots usually have limited degrees of freedom per leg. Addressing the robot whose legs have only two degrees of freedom, this paper explores several turning strategies including altering the median value, changing the phase difference, and modifying the amplitude. The insights of the proposed methods are that we break down the symmetries which exist during the process of the robot locomotion and rebuild them. Since we probe into the turning feasibility from the points of the median value, phase difference and amplitude in the sine functions, these turning methods are feature of universality. In order to evaluate these methods, this paper presents a new way to weigh the stability, which can be easily applied to practical robots. Experiments demonstrate that the quadruped turns around with little effort and endeavor.

Key words: quadruped robot; turning methods; controller; amplitude; mediam value; phase difference
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Robots in practical application should have a feature of simplicity with the target at possessing variable speed, functional agility, and minimal energy consumption. Martin Buehler presents series quadrupeds named SCOUT with only one actuator per leg after simplifying the mechanical design, control strategies, and the dynamic model [1-3]. Through open loop control, i. e., positioning the legs at a fixed angle during flight and commanding a fixed leg sweep angular velocity during stance, the quadruped robot realizes the bounding gait. Kimura and Fukuoka [4-5] realized the trotting gait in the Patrush robot and in the Tekken robot which are controlled under central pattern generator (CPG). The CPG predigests the nervous system which exists in animals. These simplicities in apparatus, in control laws, or in dynamical model lead these quadrupeds successfully down to earth walking, trotting, bounding, and turning.

Generally, there are three degrees of freedom (DOF) per leg in quadruped robots, i. e., hip yaw, hip pitch, and knee pitch, to perform various movements like turning, walking, and climbing. However, quadrupeds with two DOFs per leg [6-8] can also achieve such behaviors to simplify mechanical design or reduce control complexity or both. The robot SCOUT whose leg rotation is restricted in the sagittal plane realized turning through adding different offsets to the nominal desired hip angles at impact for the left legs and the right legs.

The robot has only two DOFs per leg, i. e., the hip pitch joint and the knee pitch joint, as shown in Fig. 1. Since both joints pivot on pitch axis, the quadruped turning cannot be taken for granted. However, the trunk rotation can compensate the missing of the hip yaw joints which is usually the key factor of quadrupeds turning. From the view of the angular position control, there exist three different ways of turning, i. e. changing the phase difference between legs, altering the median value, and modifying the amplitude.

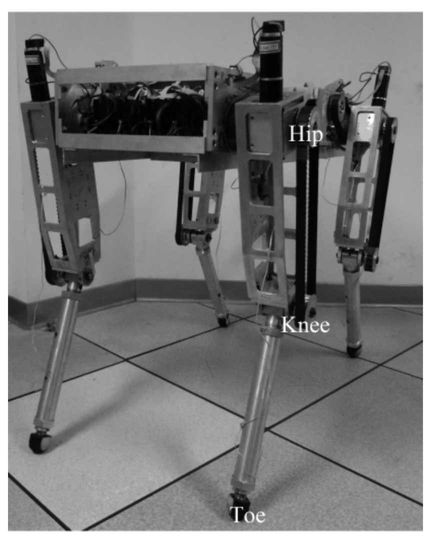

Fig. 1　Quadruped with one hip pitch joint and one knee pitch joint per leg

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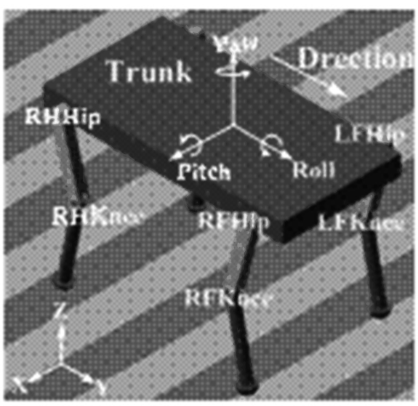
1 Robot Model and the Controller

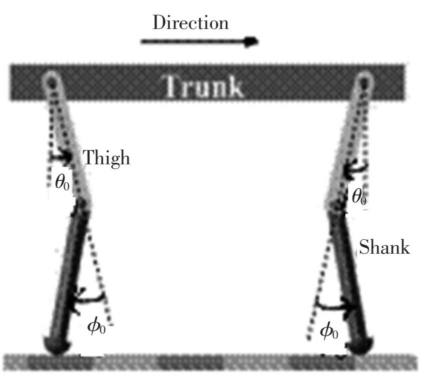
1.1 Robot Skeleton

During this research, the turning simulations are investigated on the platform composed of MSC. ADAMS and MATLAB. The software MSC. ADAMS mimics the dynamic object and the MATLAB imitates the controller.

The quadruped consists of nine parts, a trunk, two pairs of thighs and two pairs of shanks, which are illustrated in Fig. 2. In order to explore the maximal dynamic effect near to nature, the quadruped robot in the simulating environment is designed as: the length, width and height of the trunk are 1200 mm, 600 mm, and 100 mm, respectively; the length of the thigh is 350 mm; the length of the shank is 422 mm; and the total height of the quadruped is 750 mm. The legs link upon with the trunk via corresponding hip joints and the thighs join up the shanks with the knee joints. All joints pivot upon the pitch axis. The initial hip angles θ_0 are 15° which relate to the zero line normal to the horizontal plane and the initial knee angles ϕ_0 are 28° that make the toes right under the hip joints. The skeleton of the robot is showed in the next figures.



(a) The isometric view



(b) The lateral view

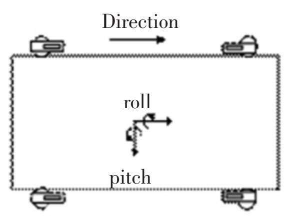
Fig. 2 Configuration of the quadruped

The capital letters appeared in the Fig. 2 represent as follows: R denotes right, L left, H hind, and F front, so the RHHip means right hind hip joint and the left front knee joint is LFKnee for short. In order to facilitate the control and the comparison of different legs, the angle directions in the lateral view in Fig. 2 regulate the positive angles to the front legs and the hind legs.

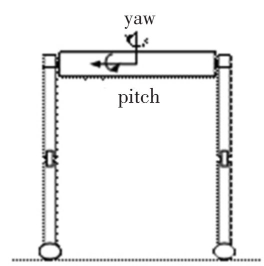
1.2 Capsule Turning Description in Kinematics

In a general way, quadruped robots adopt the hip yaw joints that rotate the legs in the transverse plane when turning. Since every leg increases one degree of freedom, the quadruped should guarantee more power supply and afford more difficulty in control.

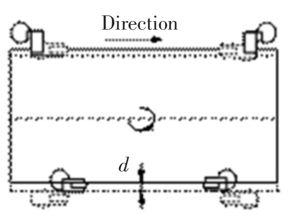
Turning requests the legs of the quadruped should not swing only in the sagittal plane when the robot moves forward. The foot should have transverse displacement, as shown in Fig. 3. If the situation which the robot spins with one of the legs fixed is excluded, the rolling of the trunk can substitute the hip yaw joint at each leg. The next figures are series pictorial diagram about the trunk rotation compensating the legs yawing.



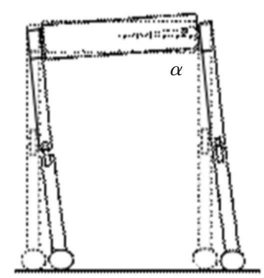
(a) The top view



(b) The front view



(c) The top view when rolling



(d) The lateral view

Fig. 3 Sketch map for the quadruped turning

The views of the quadruped straight walking from different points are expressed in Fig. 3 with solid drawings in Figs. 3 (a) and 3(b) and with dashed drawings in Figs. 3(c) and 3(d). The solid drawings in Figs. 3(c) and 3(d) depict an instant robot turning with a radius. The trunk displacement d in transverse direction increases along with the rolling angle α augmenting. As the quadruped turning involves not only kinematics but also dynamics, it is not easy to give an exact formula to ascertain the relationship between the turning radius and the trunk rolling angle α. So this subsection only presents a capsule description of the turning. Section 2 gives how the radius can be controlled under tuning the drive signals of joints.

1.3 Controller

It is necessary to concentrate on the controller generating angular position signal for joints before addressing the turning methods. Previously on this research, we have investigated the spinal CPG [10], i. e. a biological control of locomotion, which can provide open loop position control. The coupled oscillators that compose the generator have the general form:

$$\dot{x} = f(x) \tag{1}$$

where x is the state variables and f represents the dynamics of oscillators. The solution to Eq. (1) is a sinusoidal signal with time. So the outputs of CPG are sinusoidal signal actually.

To make these turning methods in general, it employs the sine functions directly that generate the walking gait for the quadruped. The target angular positions are determined as follows:

$$T_{\text{stan}} = 2N \cdot T/(N+1) \tag{2}$$

$$T_{\text{swin}} = 2T/(N+1) \tag{3}$$

$$t_{\text{RF}} = rem(t, T) \tag{4}$$

$$t_{\text{LH}} = rem(\max((t - N \cdot T/(3(N+1)) - D_{\text{LH}} \cdot T/(2\pi)), 0), T) \tag{5}$$

$$t_{\text{LF}} = rem(\max((t - 2N \cdot T/(3(N+1)) - D_{\text{LF}} \cdot T/(2\pi)), 0), T) \tag{6}$$

$$t_{\text{RH}} = rem((\max(t - N \cdot T/(N+1) - D_{\text{RH}} \cdot T/(2\pi)), 0), T) \tag{7}$$

$$H_i = \begin{cases} -HA_i \sin(2\pi t_i / T_{\text{stan}}), & 0 \leqslant t_i < T_{\text{stan}}/4 \\ -HA_i \cos(\pi(4t_i - T_{\text{stan}})/(2T_{\text{swin}})), & T_{\text{stan}}/4 \leqslant t_i < (T_{\text{stan}} + 2T_{\text{swin}})/4 \\ HA_i \cos(\pi(4t_i - T_{\text{stan}} - 2T_{\text{swin}})/(2T_{\text{stan}})), & (T_{\text{stan}} + 2T_{\text{swin}})/4 \leqslant t_i < T \end{cases} \tag{8}$$

$$K_i = \begin{cases} KA_i \sin(\pi(4t_i - T_{\text{stan}})/(2T_{\text{swin}})), & T_{\text{stan}}/4 \leqslant t_i < (T_{\text{stan}} + 2T_{\text{swin}})/4 \\ 0, & \text{others} \end{cases} \tag{9}$$

$$Hip_i = H_i + HM_i \tag{10}$$

$$Knee_i = K_i + KM_i \tag{11}$$

Where N is the ratio of the standing period to the swinging period, and $N = T_{\text{stan}}/T_{\text{swin}}$, similar to the duty factor; T is the period constant, and $T = T_{\text{stan}}/2 + T_{\text{swin}}/2$; T_{stan} and T_{swin} are the time that a leg stands on the ground and swings in the air during a period; t is the time variable; t_i is the ith leg time variable, the value of t_i is less than the value of Tand larger than 0; i is the index of four legs, i. e. , the subscript i should enumerate the names of RF, RH, LF, and LH, like that t_i may be t_{RF}; D_i is the delay phase of the ith leg, concretely the D_i represents the delay phase of the left hind leg; HM_i and KM_i are the median value of the ith hip joint and the ith knee joint; H_i and K_i are the intermediate state for the ith hip joint and the ith knee joint; HA_i and KA_i the amplitude of the ith hip joint and the ith knee joint; Hip_i and $Knee_i$ are the target angular positions of the ith hip joint and the ith knee joint, and which determine the target positions for the corresponding joints. ; $rem()$ is an real number operator.

Eqs. (2) and (3) provide different periods for the leg in the stance phase and in the swing phase, respectively. Eqs. (4) - (7) ensure the phase delay for the legs. The sine functions (8) and (9) are primary outputs without deviation for the hip joints and the knee joints, respectively. Finally, Eqs. (10) and (11) are the outputs for the hip joints and the knee joints. Tab. 1 explains the notations which appear in these equations.

Note that the default values θ_0 and ϕ_0 appeared in subsection 1.1 are the start values in the controller, which correspond to zero of the Hip_i and the $Knee_i$ when straight walking. For example, the trajectories parameters are as follows: $N = 3$, $T = 2$, $HM_i = KM_i = D_i = 0$, $HA_i = 0.1396$, $KA_i = 0.1047$, ($i = \{RF, RH, LF, LH\}$). These parameters can cause the robot to move forward at the speed of 5.2 cm/s and with the stride of 10.4 cm.

$$Speed = 2Height \cdot \tan(HA_i)/T \tag{12}$$

$$Stride = 2Height \cdot \tan(HA_i) \tag{13}$$

where *Speed* is the speed of the quadruped moving forward and *Stride* represents the stride length; *Height* corresponds to 750 cm according to subsection 1.1.

The trajectories for all the hip joints and the knee joints are shown in Fig. 4. In the figure, the dashed blue lines represent the angular trajectories of the knee joints and the solid red lines represent the trajectories of the hip joints.

2 Turning Methods and Simulations

Whether the changing of Hip-knee joints causes the robot body inclination and turning, or as M. Buehler stated in Ref. [1]: adding offsets to the nominal desired angles realizes the turning, when quadrupeds walk straightly, from the points of amplitude, phases or the median values, and there exist balances among the different hip joints and among the different knee joints. If the balances are broken down, the robots can move with curves. Three different methods for turning are brought forward as follows.

2.1 Altering the Median Value

The quadruped moves forward with its hips and knees oscillating around a median value, also called oscillation center. As exhibited in Fig. 4, the median values of all the joints are equal to zero when straightly walking. Changing some of these values results in interesting actions like up-sloping and down-sloping [10]. Turning can also be realized through modifying the right or the left median values.

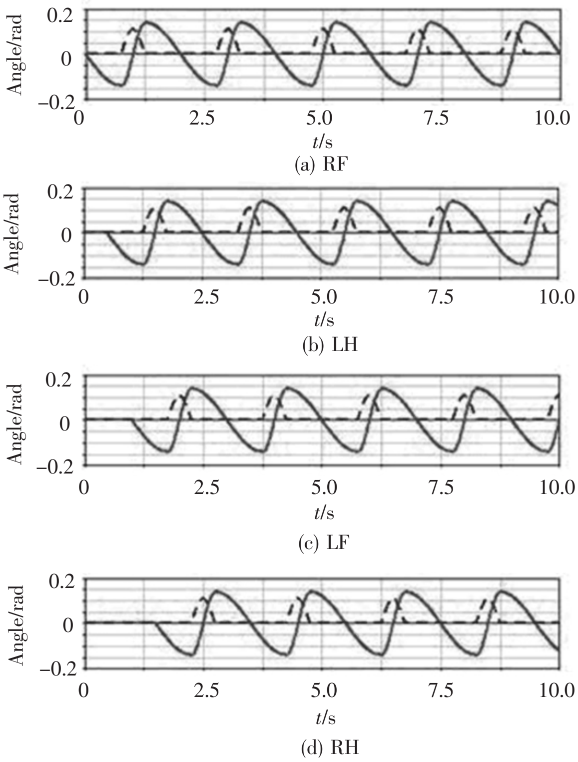


Fig. 4 Curves of the straight walking gait

The different median values in left side and in right side result in the body inclination. So, when the quadruped steps forward, there exists a trunk displacement d in the transverse plane which has been explained in subsection 1.2. The concrete parameters are given as an example for the quadruped turning by altering the median values: $N = 3$, $T = 2$, $D_i = 0$, $HA_i = 0.1396$, $KA_i = 0.1047$, $i = \{RF, RH, LF, LH\}$; $HM_{RF} = -0.1745$, $HM_j = 0$, $j = \{RH, LF, LH\}$; $KM_{RF} = KM_{RH} = 0.1309$, $KM_{LF} = 0.0486$, $KM_{LH} = 0$.

In the simulation, the robot walks forward firstly. And then during the time interval between 13.75 s and 14.5 s though adjusting these values HM_{RF}, KM_{RF}, KM_{LF} and KM_{RH} from zero to -0.1745, 0.1309, 0.0486, and 0.1309 respectively, the robot in simulations turns right side that is displayed in Fig. 5. The target trajectories of all joints are showed in Fig. 6. The values of HA_i, T and KA_i ensure the same speed and stride as straight walking.

Fig. 5 gives the pictures about the robot under the controller with parameters provided above. In the simulation, the quadruped walks straightly during the time between 0 s and 13 s and then turns right. The white thin line represents the trajectories of the center of gravity (COG).

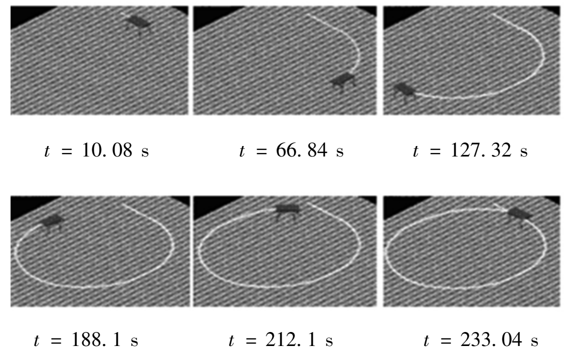


Fig. 5 Robot turns right by altering the median values

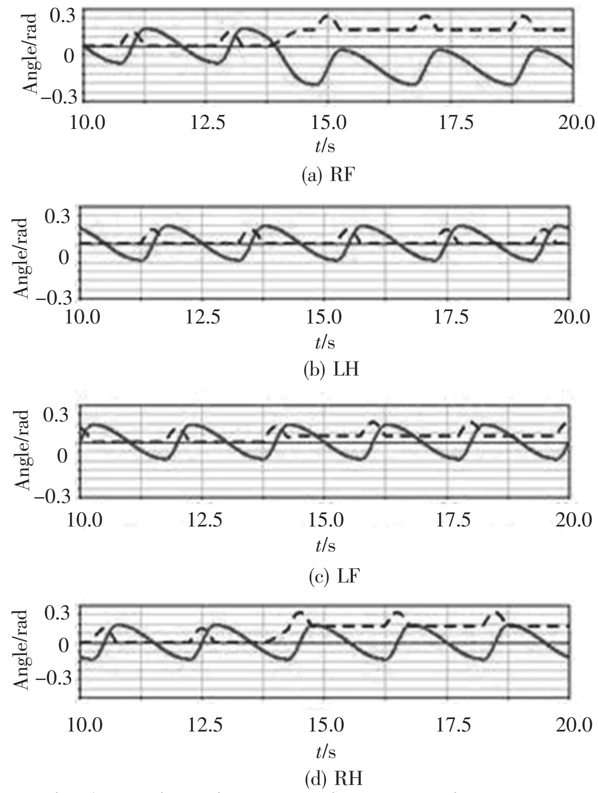


Fig. 6 Trajectories by altering the median values

2.2 Changing the Phase Difference

When quadrupeds move with a certain gait, there exist fixed phase differences between different legs. For instance, the phase differences of the walking gait are the values about $\pi/2$. Just as Fig. 4 showed that all the phase discrepancies among different legs are equals to each other if the quadruped walks straightly. It reveals that the balance in phase maintains the direct movement. Therefore, the inequality of the phase differences can leads to the quadruped turning.

In order to facilitate the comparison later, the turning time keeps in line with the last subsection. So the parameters are changed from the straight walking. That is, HM_i, HA_i, and KA_i are identical to them in straight walking. The value D_{LF} varies from 0 to $7\pi/18$ during that time interval between 13.75 s and 14.5 s. The total parameters are set here: $N = 3$, $T = 2$, $D_j = 0$, $j = \{RF, RH, LH\}$; $D_{LF} = 7\pi/18$, $HM_i = 0$, $HA_i = 0.1396$, $KA_i = 0.1047$, $i = \{RF, RH, LF, LH\}$. Fig. 7 shows the target position of all the joints.

Note that if another values are given to the D_{LF} or D_{RF}, the robot can turn with another radius too. The values in this simulation are to ensure the approximate turning radius with that in altering the median values.

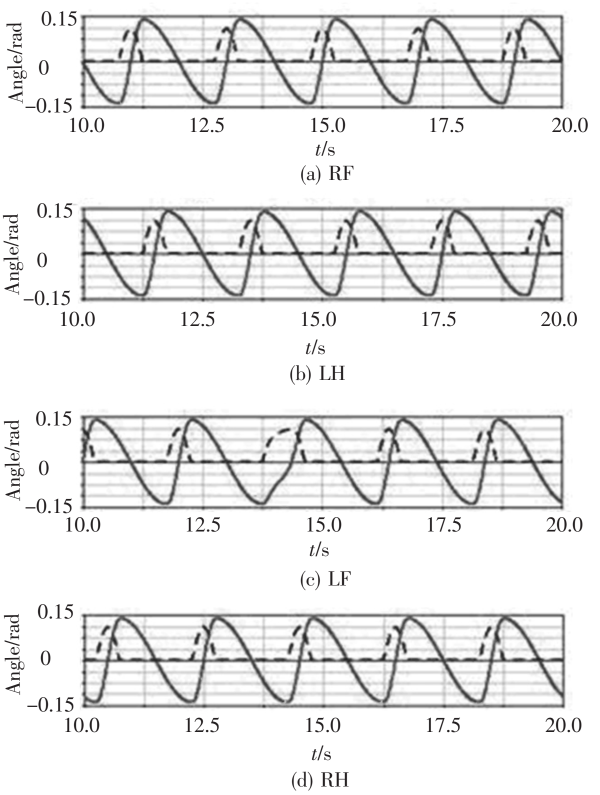


Fig. 7 Trajectories by changing the phase difference

With the control under the parameters mentioned above, the quadruped travels straight-ahead before 13 s and subsequently tunes the phase of the left front leg. Both the left front hip joint and the left front knee joint are postponed for $7\pi/18$ to stride out of the orbit similar to Fig. 5, which are displayed in Fig. 8.

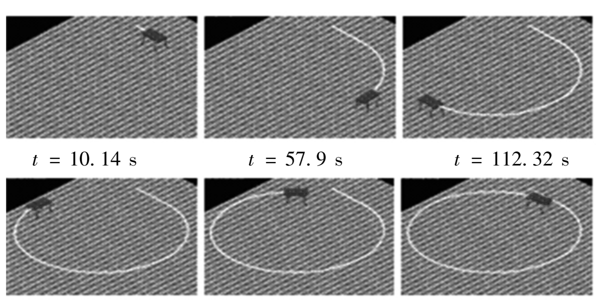


Fig. 8 Robot turns right by changing the phase difference

Under the method of changing phase differences, the quadruped walks with the LF leg and the RH leg rising at almost the same time. Meanwhile, there is a little x-axis drift after the robot circled around.

2.3 Modifying the Amplitude

As previously noted, when straightly walking, where there is one in equilibrium, there is a possibility for the quadruped to turn. It can be easily found that the amplitudes of all the joints consist of balance during the quadruped directing forward.

If the strategies of altering the median value is equal to flexing the legs and the way changing the phase difference corresponds to regulating the sequence of lifting up or touching down foots, the method by modifying amplitudes is identical with adjusting steps. It is a matter of a common observation that the left amplitude differing to the right amplitude results in the turning. This simulation transfers HA_{RF}, HA_{RH}, KA_{RF}, and KA_{RH} from 0.1396 to 0.22, 0.1396 to 0.22, 0.1047 to 0.192, and 0.1047 to 0.1833, respectively. The following shows the curves in Fig. 9 and lists the parameters.

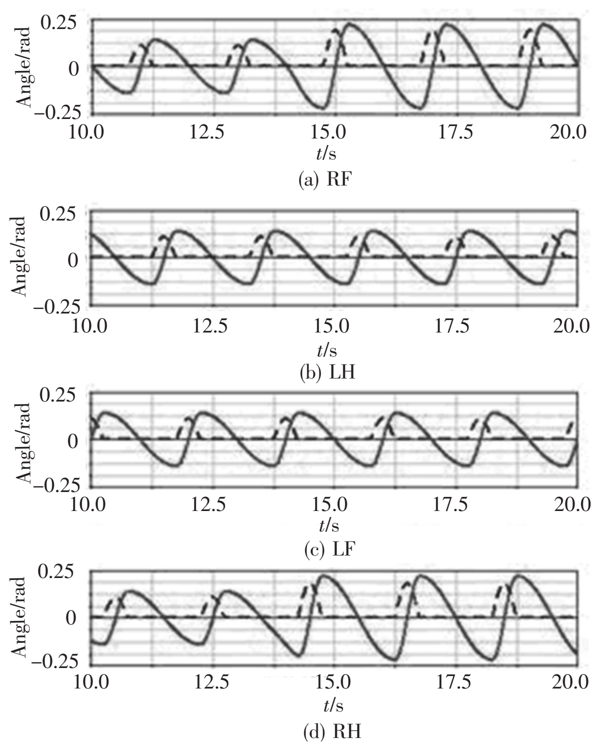


Fig. 9 Trajectories by modifying the amplitude

The parameters: $N = 3$, $T = 2$, $D_i = 0$, $HM_i = KM_i = 0$, $i = \{RF, RH, LF, LH\}$; $HA_j = 0.1396$, $KA_j = 0.1047$, $j = \{LF, LH\}$; $HA_{RF} = 0.22$, $HA_{RH} = 0.22$, $KA_{RF} = 0.192$, $KA_{RH} = 0.1833$.

After modified the amplitudes of the joints, the quadruped turns right after 15 s and steps out an elliptical curve.

3 Evaluations and Discussions

The basic requirement of a walking robot is to provide stable motion, i. e., to keep the movement between a period of time without falling down. In order to measure the stability, a common way calculates the shortest distance from the COG or the ZMP of the quadruped to the boundaries of the support polygon formed by the horizontal projection of the standing foots. However, there must be an unstable time of duration in the robot with 2 DOFs. In fact, robots with high gain position control can still move forward.

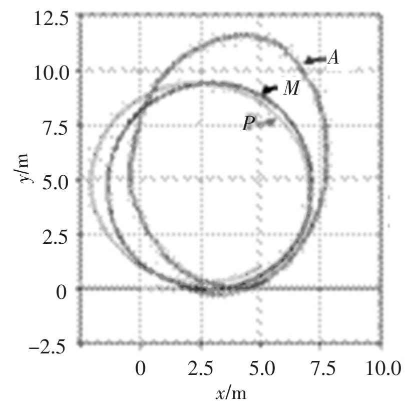
This research introduces the rolling angle, the pitching angle, and the z-axis displacement to evaluate the stability of the robot. According to Fig. 2 (a), the rolling angle is defined by the trunk rotation angle along the rolling axis with anti-clockwise, the pitching angle is defined by the rotation angle along the pitching axis with anti-clockwise, and the z-axis displacement is the displacement about the center mass of the trunk along the z-axis in the xyz coordinate system. It is not easy for the mammal-like robot to fall down in the sagittal plane, but it is easy to roll down in the coronal plane. Then the rolling angle becomes an important indicator to evaluate one gait. Normally, the rolling angle should not exceed 5°. These concepts possess the advantages that can be easily realized in engineering.

Under these methods stated in Section 2, the COG curves around with circles whose radiuses are close to each other. Fig. 10 (a) shows the trajectories of the COG. The zeros showed in Figs. 10(b) and (c) are the initial postures displayed in Fig. 2 (a) with respect to the rolling angle or the pitching angle. The zero in z-axis displacement represents the center mass of the trunk in the initial state in Fig. 10 (d).

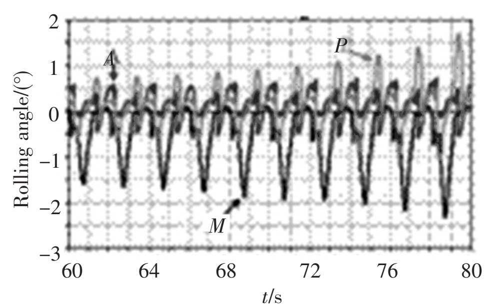
These curves in Fig. 10 (a) are close to a round circle whose radius is about 5 m. Because it is hard to break down the symmetry formed during straight walking, there is a length of line-like movement in the method A. But it does not affect the comparison. Fig. 10 (a) shows the trajectory of the COG under the method A fiercely swings back and forth, whereas the trajectory under the method P has an even and gentle movement. This phenomenon indicates that the method P makes the quadruped more stable than the method A.

As stated previously in Section 1.2, the trunk rolling results in the turning. Fig. 10 (b) displays that the method M and the method P both have 1° or 2° rotation, whereas the method A has about 1° rotation. This explains why the quadruped takes more time to circle around in the method A.

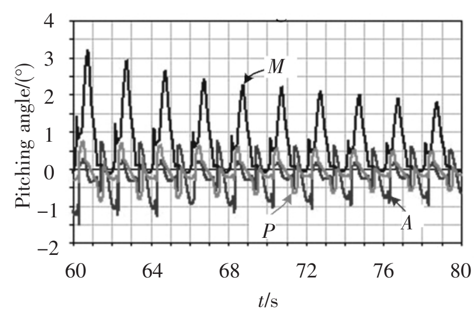
Due to the fact that the quadruped always bends one side of joints under the method M, the curves M in Figs. 10 (c) and (d) oscillate sharply. It is clearly seen that the robot with the method M tumbles more easily than that with the method P when it speeds up.



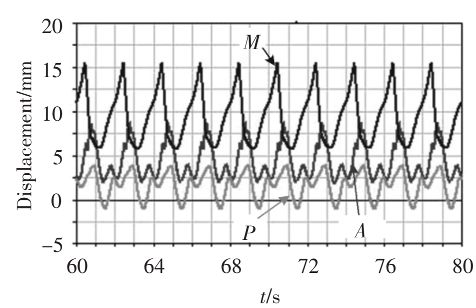
(a) Trajectories of the COG



(b) Rolling angle of the quadruped



(c) Pitching angle of the quadruped



(d) Displacement of the COG

Note: M-the turning method of altering median values, the method M is used for short later; A-the method about modifying the amplitudes, the method A for short; P-the turning method of changing the phase, the method P for short

Fig. 10 Comparisons among these turning methods

In spite of the sequence of the leg movement which cannot be defined as walking gait, strictly speaking, the quadruped with the method P possesses a symmetric pitching angle and least displacement in the z-axis direction. After a generalized consideration of all the merits and demerits, the method P is an ideal choice for quadruped robot turning without hip yaw degree when turning.

4 Conclusions

Three methods about turning from different points are explored based on the quadruped robot with 2 DOFs. The key of these methods is to find out the symmetries which exist during the process of the robot moving forward and break down them and rebuild them. All the methods successfully actuate the quadruped to step out a right ring.

These methods can be realized through the sinusoidal controller that proposed in this paper or can be realized through CPG means which have been popular in the position control. If the CPG is used, the output signals from CPG should be substituted by the Hip_i and the $Knee_i$ in this paper. These turning strategies can also be applied to the trotting gait for the quadruped.

These strategies do not conflict against each other. The contrary, they can compensate mutually to offset the crook in the path or to strengthen the tortuous trajectories through appropriate utilization. In the future, we will explore the kinetics of the robot and its feet contact model to enhance the controllability and the robustness without the localization of realizing the methods.

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