doi:10.3772/j.issn.1006-6748.2014.03.010

Analysis on pivot turning of quadruped robot with bionic flexible body driven by the PAMs①

Lei Jingtao (雷静桃)②, Yu Huangying, Wu Zhizheng
(School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200072, P. R. China)

Abstract

The pivot turning function of quadruped bionic robots can improve their mobility in unstructured environment. A kind of bionic flexible body mechanism for quadruped robot was proposed in this paper, which is composed of one bionic spine and four pneumatic artificial muscles (PAMs). The coordinated movement of the bionic flexible body and the leg mechanism can achieve pivot turning gait. First, the pivot turning gait planning of quadruped robot was analyzed, and the coordinated movement sequence chart of pivot turning was presented. Then the kinematics modeling of leg side swing and body bending for pivot turning was derived, which should meet the condition of the coordinated movement between bionic flexible body and leg mechanism. The PAM experiment was conducted to analyze its contraction characteristic. The study on pivot turning of the quadruped robot will lay a theoretical foundation for the further research on dynamic walking stability of the quadruped robot in unstructured environment.

Key words: quadruped robot, bionic flexible body, pivot turning, pneumatic artificial muscle (PAM)

0 Introduction

Walking in the unstructured environment such as barriers, trenches and so on, quadruped robots need the function of pivot turning. Many kinds of quadruped robots have been developed, which mainly include periodic gait, such as crawl gait[1] and trot gait[2]. But it is necessary to study the pivot turning gait for quadruped robots suitable for the unstructured environment.

The super athletic ability of the four-legged creatures provide a good biological template for developing quadruped bionic robots, which is the collaboration of the nervous, musculature and skeletal systems[3]. The walking mobility and stability of the four-legged creatures depend on their trunk property, whose spine is a complex mechanical structure. The trunk spine of the four-legged creature consists of vertebras, which are separated by intervertebral discs. Therefore the trunk of the four-legged creature has a flexible body property, which can bend in two-dimensional direction for adapting various complicated terrains. The coordination movement between the flexible body and the leg mechanism of creatures can go across obstacles or pivot turning quickly.

In the unstructured environment, the terrain is complicated and diversified. The mobility and stability of the quadruped robot depend on the body mechanism. The body properties of the developed quadruped robots are generally rigid. The body role during dynamic walking or pivot turning has been usually ignored[4]. Some researchers have paid more attention to the flexible body structure since 2009. Remy[5] proposed a new mechanism to increase the adjustable quality on the rigid body to change the centroid positions, which reflects the trunk properties of four-legged creatures during dynamic walking. A kind of segmented flexible spine was proposed for a humanoid robot to maintain its dynamic walking stability[6]. A kind of bionic body with variable stiffness was designed and the robot dynamic stability of the flexible body structure was analyzed[7,8]. A kind of variable viscoelastic body was developed and the coordinated movement between body and leg mechanism was studied to achieve dynamic stable walk[9,10]. A method was proposed to add a joint in the middle of the robot body to improve its flexibility[11]. Therefore, for quadruped walking robots, the body flexibility structure should not be ignored, which plays an important role for quadruped robots dynamic

① Supported by the National Natural Science Foundation of China (No. 51375289), Shanghai Municipal National Natural Science Foundation of China (No. 13ZR1415500) and the Innovation Fund of Shanghai Education Commission (No. 13YZ020).
② To whom correspondence should be addressed. E-mail: jtlei2000@163.com
Received on Nov. 12, 2013

stable walking in the unstructured environment. The body properties directly affect the mobility and dynamic stability of quadruped robots.

In this paper, a kind of bionic flexible body mechanism driven by PAMs for quadruped robot is proposed based on the biological principles of four-legged creatures' trunk properties. The gait planning of the pivot turning is analyzed. Then the kinematics of pivot turning is derived to determine the joints angular displacement and obtain the relationship between PAM and the body bending angle. The PAM experiment is also conducted to study its working characteristic, which will lay the foundation for developing quadruped robot walking in the unstructured environment.

1 The biological principles

The movement of the creatures is the result of cooperation and coordination of nervous, musculature and skeletal systems, of which the nervous system controls the movement of the muscular system to produce force acting on the skeletal system. Then the skeletal system drives the joints to rotate relatively and achieve a variety of movement[3].

The muscle of the creatures is a kind of special structure, which is composed of a large number of sarcomeres, their series form muscle fibers, and muscle fibers in parallel form muscle. When the nervous system stimulates these sarcomeres, they can absorb the chemical energy in the muscle and their length changes. Consequently the muscles begin contraction and drive connected bones, and then complete a variety of movement[12].

By observing the body properties of four-legged creatures walking in the unstructured environment, we can find that their flexible body plays an important role, especially when creatures are in face of the obstacles and they have to make a pivot turning. The creatures' body can bend at an angle so that they can finish pivot turning quickly[13], as shown in Fig. 1.

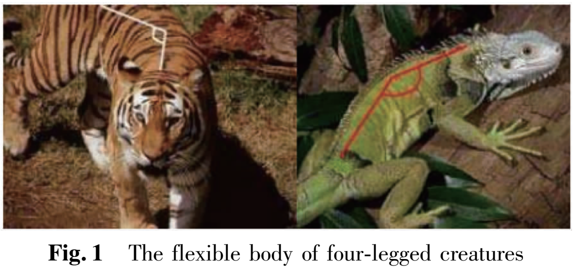


Fig. 1 The flexible body of four-legged creatures

One method to analyze the four-legged creatures' walking pattern is to gather actual motion data. In order to learn more about the pivot turn gait principle of the creatures, and the coordinated movement between the trunk and leg mechanism, the high-speed motion capture experimental method can be used to study creatures' body bending and legs swing. The specific method is as follows. Based on the principles of computer vision, the optical motion capture and the analysis system is used to monitor and track the specific spots by the synchronization and calibration camera, which are pasted along the creature flexible trunk and on the leg joints. According to the collected data, the motion decomposition can be done to analyze how the creature keep dynamic stable when walking in the unstructured environment. By analyzing the variable topology configuration transformation of four-legged creatures during dynamic stable walking, we can conclude that the flexible trunk has the bending characteristic along two different directions, and can obtain the kinematics parameters of coordination movement between trunk and legs, which will provide valuable reference for developing quadruped bionic robot.

2 The structure of the robot

A kind of bionic quadruped robot is presented as shown in Fig. 2. The robot is composed of four leg mechanisms and one bionic body mechanism driven by PAMs. Each leg has three rotary joints, which are side swing hip joint, walking hip joint and knee joint. Each joint of the leg mechanism is driven by a DC motor. The leg mechanism and the body are connected by the side swing hip joint. The bionic body is composed of a forebody, a hind body, a bionic spine and four PAMs. The forebody and hind body are connected by the bionic spine and PAMs. The PAM can imitate the behavior of biological muscle and achieve the relative motion of the forebody and hind body.

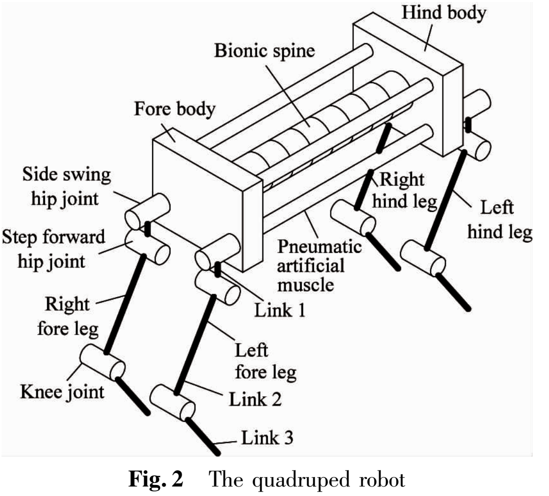
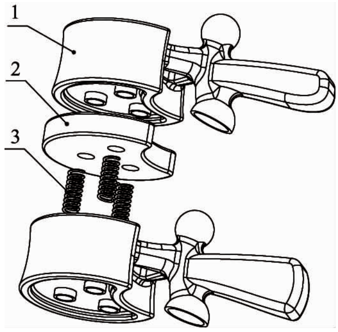


Fig. 2 The quadruped robot

The bionic body bending is driven by PAMs. The PAM has remarkable muscle-like properties such as softness and flexibility, which consists of thin rubber tube covered by high strength braided fibers. One end has a gas inlet/outlet and the other is connected with the load. As the PAM is supplied with compressed air, the inner bladder expands in the radial direction and the PAM contracts or shortens to create a force in the longitudinal direction.

The artificial spine consists of a number of bionic spine units. Each bionic spine unit consists of biomimetic vertebra, intervertebral disc and three springs, as shown in Fig. 3. The intervertebral disc is designed between two biomimetic vertebras. Three springs pass through the intervertebral disc and connect two adjacent biomimetic vertebras. The structure can obtain flexible spine and achieve body bending in two-dimensional space.



1. Biomimetic vertebra; 2. Intervertebral disc; 3. Spring

Fig. 3 The bionic spine unit

3 Gait planning of pivot turning

The sequence chart of pivot turning gait of the quadruped robot is shown in Fig. 4.

① The initial state, as shown in Fig. 4(a).

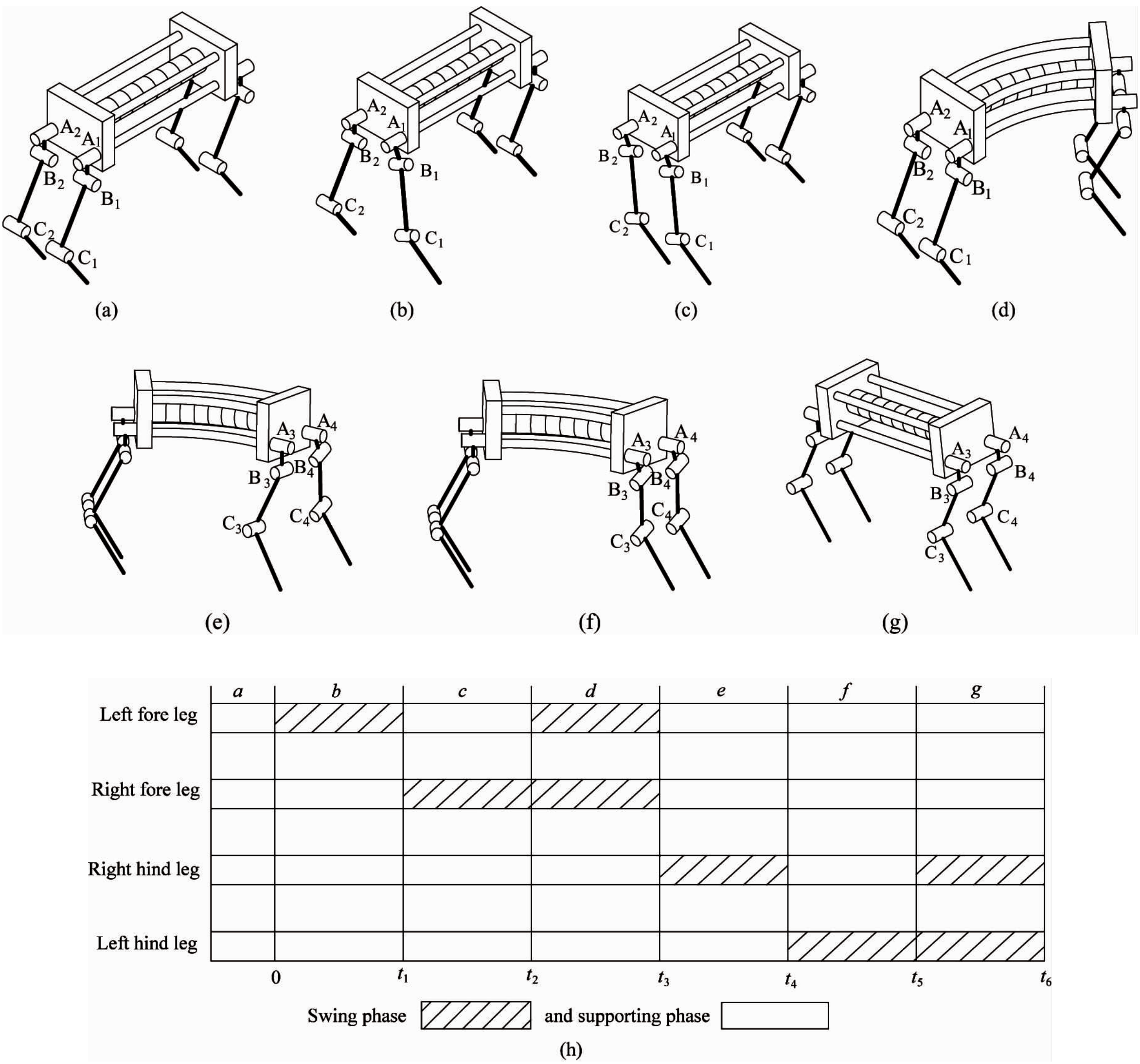


Fig. 4 Gait planning of pivot turning

② The left foreleg begins with the side swing and finally the foot-end touches the ground, as shown in Fig. 4(b).

③ The right foreleg begins with the side swing and finally the foot-end touches the ground, as shown in Fig. 4(c).

④ The two forelegs begins with the side swing backward at the same time, and the body begins bending driven by the PAMs, as shown in Fig. 4(d).

⑤ The right hind leg begins with the side swing and finally the foot-end touches the ground, as shown in Fig. 4(e).

⑥ The left hind leg begins with the side swing and finally the foot-end touches the ground, as shown in Fig. 4(f).

⑦ The two hind legs begin with the side swing backward at the same time, and the body begins straightly driven by the PAMs, as shown in Fig. 4(g).

Thus a movement of pivot turning is completed. During the pivot turning, the phase of each leg changes between the swing phase and the supporting phase as shown in Fig. 4(h). Repeating the process above, gait cycle one of pivot turning can be completed.

4 Kinematics analysis

When quadruped robot begins pivot turning, the leg mechanism begins side swing as along as the bionic body bends. The bionic body is driven by PAMs. So it is necessary to analyze the coordinated movement relationship between bionic body and leg mechanisms.

4.1 Kinematics of leg mechanism

4.1.1 Forward kinematics

The Denavit-Hartenberg coordinate systems are shown in Fig. 5. The coordinate system $o_0x_0y_0z_0$ is located at the hip joint of the side swing. The coordinate frame $o_4x_4y_4z_4$ is located at the foot-end.

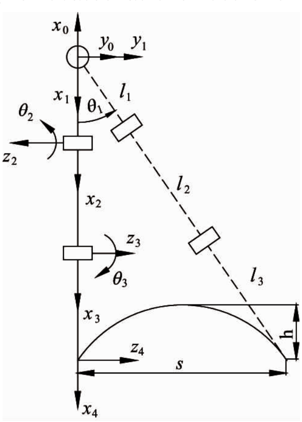


Fig. 5 The coordinate frames for kinematics modeling

According to the coordinate systems, the link parameters can be determined as shown in Table 1.

Table 1 D-H parameters

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	l_1	90°	0	θ_2
3	l_2	180°	0	$\theta3$
4	l_3	0	0	0

According to the homogeneous transformation matrix

$$ {}^{i-1}_{i}\mathbf{T} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i c\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

the transformation matrix of each link can be calculated as follows:

$$ {}^{0}_{1}\mathbf{T} = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{1}_{2}\mathbf{T} = \begin{bmatrix} c_2 & -s_2 & 0 & l_1 \\ 0 & 0 & -1 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{2}_{3}\mathbf{T} = \begin{bmatrix} c_3 & -s_3 & 0 & l_2 \\ -s_3 & -c_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{3}_{4}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & l_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The position and orientation of the foot-end with respect to frame $x_0y_0z_0$ can be described by the homogeneous transformation matrix ${}^{0}_{4}\mathbf{T}$.

$$ {}^{0}_{4}\mathbf{T} = {}^{0}_{1}\mathbf{T}(\theta_1) \cdot {}^{1}_{2}\mathbf{T}(\theta_2) \cdot {}^{2}_{3}\mathbf{T}(\theta_3) \cdot {}^{3}_{4}\mathbf{T} = \begin{bmatrix} n_x^1 & o_x^1 & a_x^1 & p_x^1 \\ n_y^1 & o_y^1 & a_y^1 & p_y^1 \\ n_z^1 & o_z^1 & a_z^1 & p_z^1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

$$ n_x^1 = c_1 s_2 s_3 + c_1 c_2 c_3 $$
$$ n_y^1 = s_1 s_2 s_3 + s_1 c_2 c_3 $$
$$ n_z^1 = s_2 c_3 - c_2 s_3 $$
$$ o_x^1 = c_1 s_2 c_3 - c_1 c_2 s_3 $$
$$ o_y^1 = s_1 s_2 c_3 - s_1 c_2 s_3 $$
$$ o_z^1 = -c_2 c_3 - s_2 s_3 $$
$$ a_x^1 = -s_1,\ a_y^1 = c_1,\ a_z^1 = 0 $$
$$ p_x^1 = l_1 c_1 + l_3(c_1 s_2 s_3 + c_1 c_2 c_3) + l_2 c_1 c_2 $$
$$ p_y^1 = l_3(s_1 s_2 s_3 + s_1 c_2 c_3) + l_1 s_1 + l_2 s_1 c_2 $$
$$ p_z^1 = l_2 s_2 - l_3(c_2 s_3 - s_2 c_3) $$

where $s_i = \sin\theta_i$, $c_i = \cos\theta_i$, $i = 1,2,3$.

4.1.2 Inverse kinematics

The forward kinematics equation has been derived as Eq. (1). The inverse kinematics of leg side swing for quadruped robot can be calculated by an inverse transformation method. The position and orientation of the foot-end is known as the following matrix:

$$ {}_1^0\mathbf{T}(\theta_1)\cdot{}_2^1\mathbf{T}(\theta_2)\cdot{}_3^2\mathbf{T}(\theta_3)\cdot{}_4^3\mathbf{T}=\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

Each side of the equation above is multiplied by the matrix ${}_1^0\mathbf{T}^{-1}(\theta_1)$, we then obtain

$$ {}_2^1\mathbf{T}(\theta_2)\cdot{}_3^2\mathbf{T}(\theta_3)\cdot{}_4^3\mathbf{T}= {}_1^0\mathbf{T}^{-1}(\theta_1)\cdot\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Three joint angular displacements can be derived as:

$$ \begin{aligned} \theta_1 &= \arctan(p_y/p_x) \\ \theta_2 &= \arctan\frac{m}{n}+\arctan\left(\frac{\sqrt{n^2+m^2-h^2}}{h}\right) \\ \theta_3 &= \theta_2-\arcsin\frac{p_z-l_2s_2}{l_3} \end{aligned} \tag{4} $$

where $m = 2l_2p_z$, $n = 2l_2p_xc_1 + 2l_2p_ys_1 - 2l_1l_2$, $h = p_x^2c_1^2 + p_y^2s_1^2 + 2p_xp_ys_1c_1 - 2l_1p_xc_1 - 2l_1p_ys_1 + l_1^2 + p_z^2 + l_2^2 - l_3^2$

The sinusoidal function is selected as the foot-end trajectory of the leg side swing. According to the length of the leg mechanism in initial state, the foot-end trajectory function is set as follows:

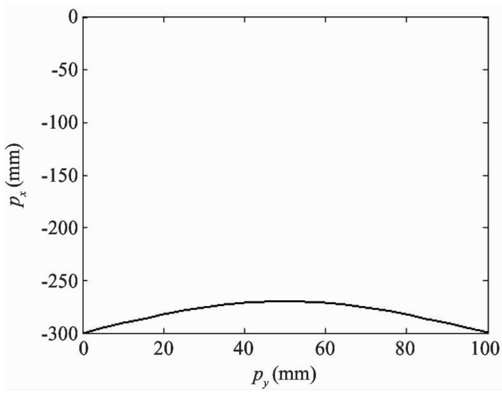
$$ \begin{aligned} p_x &= -300 + h\sin\left(\frac{\pi}{5}t\right) \\ p_y &= \frac{s}{T}t, \quad t\in[0,\ T] \end{aligned} \tag{5} $$

With the step height h = 30mm, the step length s = 100mm and one side swing cycle T = 10s, the foot-end trajectory of leg side swing is calculated as shown in Fig. 6(a). Three links' lengths are l_1 = 50mm, l_2 = 200mm and l_3 = 150mm, respectively. Then three joints' angular displacements are calculated as shown in Fig. 6(b).

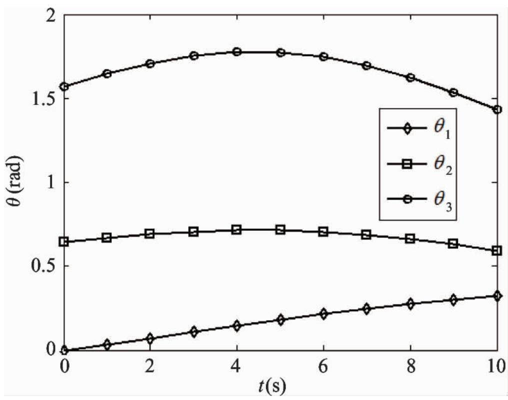
4.2 Kinematics of body mechanism

4.2.1 The bending model of the bionic body

The bending model of the bionic flexible body is shown in Fig. 7(a). The layout of four PAMs is shown in Fig. 7(b). When PAMs are filled with compressed air, the bionic body starts to bend. The dash line indicates the body state before bending, and the solid line indicates the body state after bending. The bending radius of the bionic spine is R and the body bending angle is θ, then the angle between the forebody and the hind body is 2θ.

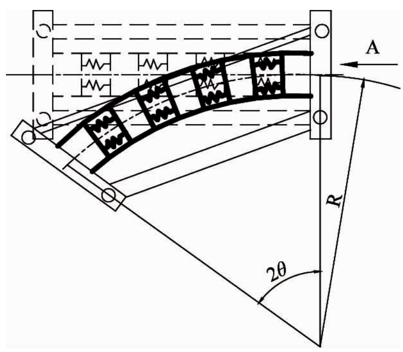


(a) Side swing trajectory of the foot-end

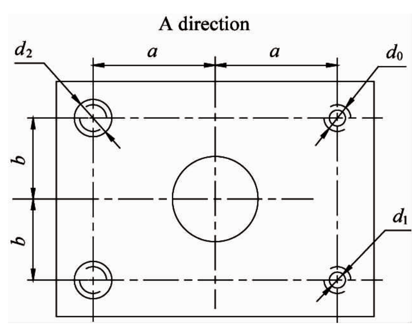


(b) Angular displacements of three joints

Fig. 6 Kinematics analysis results



(a) Body bending



(b) Layout of four PAMs

Fig. 7 Bending model of the bionic body

The original diameter and length of the PAMs are d_0 and l_0. The diameters of the stretched PAMs and the compressed PAMs are d_1 and d_2.

4.2.2 Analysis results

The geometric method is adopted to analyze the relationship among body bending angle, PAM length and gas pressure.

The geometric relationship of the bending body driven by the PAMS is shown in Fig. 8. The displacement of the bionic spine endpoint E along two directions is s_1 and s_2.

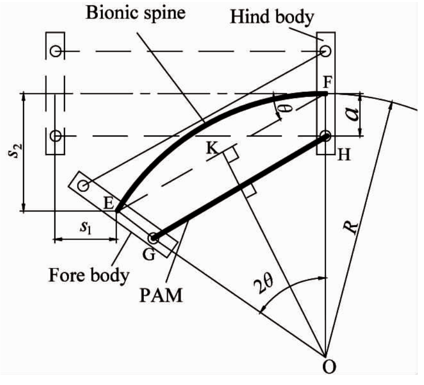


Fig. 8 Geometric relationship of the bending body

The relationship between body bending angle θ and PAM length l can be derived as

$$l = \frac{l_0 \sin\theta}{\theta} - 2a\sin\theta \quad (6)$$

Eq. (6) represents that the relationship between the body bending angle and the real-time length of PAM is almost reversely proportional. The shorter PAM length, the greater the body bending angle is. But the body bending angle should be controlled within a reasonable range, which can ensure the coordinated movement between the body and legs and meet the stable walking condition. According to Fig. 8, the displacements of point E along two directions are

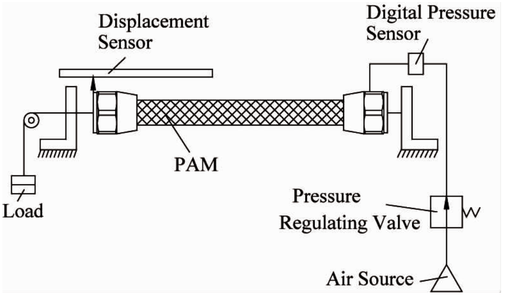
$$\begin{aligned} s_1 &= l_0 - l_{OE}\sin 2\theta = l_0 - 2\theta l_0 \sin 2\theta \\ s_2 &= l_{OF} - l_{OE}\cos 2\theta = 2\theta l_0 - 2\theta l_0 \cos 2\theta \end{aligned} \quad (7)$$

These two values should be equal to the foot-end displacement of the leg side swing. So Eq. (7) also represents the relationship between the body bending angle and the foot-end displacement of leg side swing. The coordinated movement of the leg side swing and body bending should meet the dynamic stability conditions in order to achieve pivot turning.

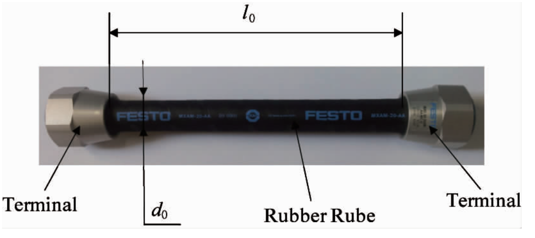
5 Experimental results

The PAM is becoming increasingly popular because of its working characteristics similar to the animal muscle. It has been used in various robots to enhance strength and mobility [14,15].

The pneumatic experimental system is designed to study the working characteristic of PAM, and to determine the relationship between the real length and gas pressure. The experimental system consists of PAM, digital pressure sensor, displacement sensor and pressure regulating valve, as shown in Fig. 9(a). One end of PAM is supplied with compressed air, and the other end is mounted a displacement sensor, which is used to measure the real length of PAM.



(a) Contraction experiment of PAM



(b) The PAM used in the experiment

Fig. 9 PAM experiment setup

The PAM (MAS-20-200N-AA-MC-O) is shown in Fig. 9(b), which is supplied by Festo company. The initial length l_0 is 200mm and the initial diameter d_0 is 20mm.

The experiment is conducted to verify the performance of PAM and its contraction characteristic. The experiment is repeated for several levels of pressures in the range from 0 to 7bar. The experimental data of length and pressure are measured several times.

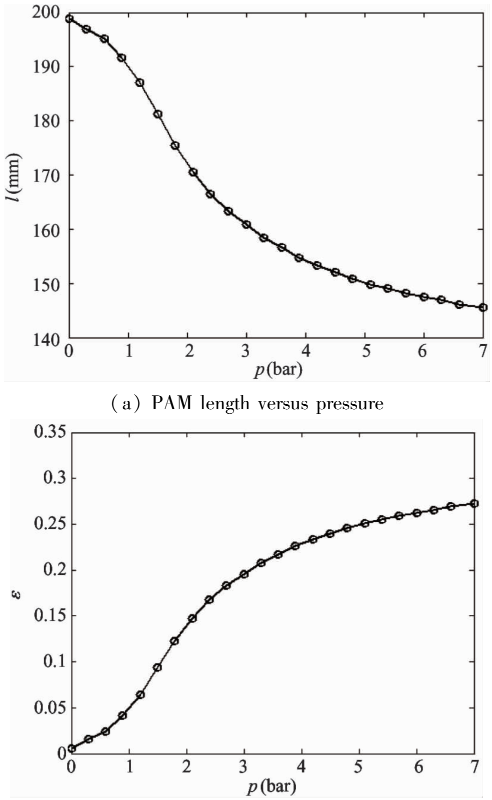
The contraction ratio of PAM can be calculated as

$$\varepsilon = \frac{l_0 - l}{l_0} \quad (8)$$

where l_0 is the initial length, l is the real-time measured length, and ε is the contraction ratio.

The relationship between the length and gas pressure, and the relationship between the contraction ratio and gas pressure are shown in Fig. 10.

PAM exhibits non-linear characteristic, which is related to the elasticity and the friction among the rubber, the braid and the end constraints. The experiment results show that the contraction characteristic and the



(a) PAM length versus pressure

(b) Contraction ratio versus pressure

Fig. 10 Experimental results

contraction length can meet the need of the pivot turning of the quadruped robot.

6 Conclusions

It is necessary for quadruped robots to have flexible body in order to adapt to the unstructured environments. A kind of bionic flexible body mechanism for quadruped robot is proposed based on the mobility principle of four-legged creatures, which is composed of one bionic spine and four PAMs. Only with the coordinated movement between the bionic flexible body and the leg mechanism, the robot can accomplish a pivot turning. The gait planning of pivot turning for quadruped robot is presented, and the kinematics of leg side swing and body bending are analyzed. The relationship between the body bending angle and the inflated real-time length of PAM is derived. The PAM experiment is conducted to study the relationship between the PAM length and the gas pressure. The experimental results show that the selected PMA meets the need of the body bending for robot pivot turning. The study will lay a theoretical foundation for further study on dynamical pivot turning behavior of the quadruped robot in unstructured environment. The control system of the bionic flexible body and pivot turning experiments of the quadruped robot will be studied in the future.

References

[1] Heeseon H, Youngil Y. Dynamic crawl gait algorithm for quadruped robots. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Nice, France, 2008. 1507-1512

[2] Meek S, Kim J, Anderson M. Stability of a trotting quadruped robot with passive, underactuated Legs. In: IEEE International Conference on Robotics and Automation, Pasadena, USA, 2008. 19-23

[3] Dai Z D. Biomimetics of legged locomotion on unstructured multi-bar compound: present situation, key technology and future development, *Journal of Nanjing University of Aeronautics & Astronautics*, 2012, 44(5):621-627

[4] Shibendu S R, Dilip K P. Soft computing-based expert systems to predict energy consumption and stability margin in turning gaits of six-legged robots. *Expert Systems with Applications*, 2012,39(5):5460-5469

[5] David C R, Keith B, Roland S. Stability analysis of passive dynamic walking of quadrupeds. *The International Journal of Robotics Research*, 2009,29(9):1-13

[6] Or J. A hybrid CPG-ZMP control system for stable walking of a simulated flexible spine humanoid robot, *Neural Networks*, 2010,23(3):452-460

[7] Tsujita K, Miki K. A study on trunk stiffness and gait stability in quadrupedal locomotion using musculoskeletal robot. In: The 15th International Conference on Advanced Robotics (ICAR), Tallinn, Estonia, 2011. 316-321

[8] Miki K, Tsujita K. A study of the effect of structural damping on gait stability in quadrupedal locomotion using a musculoskeletal robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vilamoura, Portugal, 2012. 1976-1981

[9] Katsuyoshi T, Toshiya K, Tatsuya M. Feasibility study on stability of gait patterns with changable body stiffness using pneumatic actuators in quadruped robot, *Advanced robotics*, 2009,23:503-520

[10] Takashi T, Masahiro I, Tatsuya M. Facilitating multi-modal locomotion in a quadruped robot utilizing passive oscillation of the spine structure. In: The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, China, 2010. 4940-4945

[11] Deng Q, Wang S G, Xu W, etal. Quasi passive bounding of a quadruped model with articulated spine. *Mechanism and Machine Theory*, 2012, 52 (6). 232-242

[12] Wang Z J. Theoretical study on muscle contraction. *China Journal of Bioinformatics*, 2012, 9: 208-210

[13] Park S H, Kim D S, Lee Y J. Discontinuous spinning gait of a quadruped walking robot with waist-joint. In: IEEE/ RSJ International Conference on Intelligent Robots and Systems (IROS), Alberta, Canada, 2005. 2744-2749

[14] Zhang Y S, Liu M C, Zh N, et al. The course of the development of mckibben pneumatic artificial muscles, *Chinese Hydraulics & Pneumatics*, 2008, (7):13-15

[15] Tomoyuki M, Nobutaka T, Takayuki K, et al. Spring-damper model and articulation control of pneumatic artificial muscle actuators. In: Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics (ROBIO), Phuket, Thailand. 2011. 1267-1272

Lei Jingtao, born in 1970. She received her Ph. D degree from Beihang University in 2007. She also received her B. S. and M. S. degrees from Henan University of Science and Technology in 1991 and 1996 respectively. Her research interests include the robot mechanisms and robot modular technology.