Artificial Leg Design and Control Research of a Biped Robot with Heterogeneous Legs Based on PID Control Algorithm

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Abstract: *A biped robot with heterogeneous legs (BRHL) is proposed to provide an ideal test-bed for intelligent bionic legs (IBL). To make artificial leg gait better suited to a human, a four-bar mechanism is used as its knee joint, and a pneumatic artificial muscle (PAM) is used as its driving source. The static mathematical model of PAM is established and the mechanical model of a single degree of freedom of a knee joint driven by PAM is analyzed. A control simulation of an artificial leg based on PID control algorithm is carried out and the simulation results indicate that the artificial leg can simulate precisely a normal human walking gait.*

Keywords: *Biped robot with heterogeneous legs, Artificial leg, Pneumatic artificial muscle, PID control algorithm.*

Introduction

The 2nd national sampling investigation of the disabled indicated that there are at least 24120 thousand people with physical disabilities in China and the lower limb amputees are about 440 thousand [6]. It is important for amputees to be able to install lower limb prostheses, which can contribute to compensating their basic motion functions. With the development of computer technology, intelligent bionic legs controlled by microprocessors came into use for the disabled and a lot of achievements were obtained in the 1990s. Relevant platforms are needed during the development process of IBL to evaluate product performance. To evaluate IBL performance, repetitive walking tests of amputees with IBL are necessary. However, IBL tests can be exhausting to amputees. They are not only costly but also painful to human subjects. They may even lead to accidental harm to amputees.

During the development of IBL, a dedicated experimental platform was designed, as shown in Fig. 1 [5]. The experimental platform can reproduce human hip motion and drive the IBL to test its swing and stance performance. Since its hip point is fixed, it cannot be used to test walking dynamic characteristics, including walking stability, human-computer coordination and gait tracking of IBL to the healthy leg of the disabled.

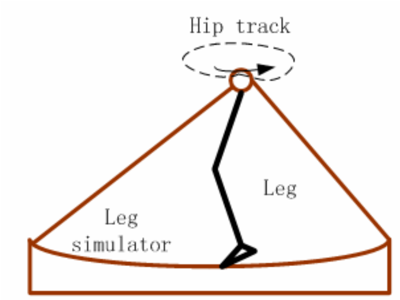

Fig. 1 Prosthetics experimental platform

In view of the considerations above, a biped robot with heterogeneous legs [1] is proposed as a new platform for the research of IBL, as shown in Fig. 2. Two legs are included in BRHL: one is an artificial leg with 6 degrees of freedom (3 DOF hip, 1 DOF knee and 2 DOF ankle), and the other one is a bionic leg with 4 degrees of freedom (3 DOF hip, 1 DOF knee). The bionic leg is composed of a hip joint and IBL with a static prosthetic foot. The artificial leg is corresponding to the amputee's healthy leg and the bionic leg is corresponding to the intelligent prosthesis used by amputees. So BRHL can simulate amputees' walking with IBL well and is an ideal test-bed for IBL.

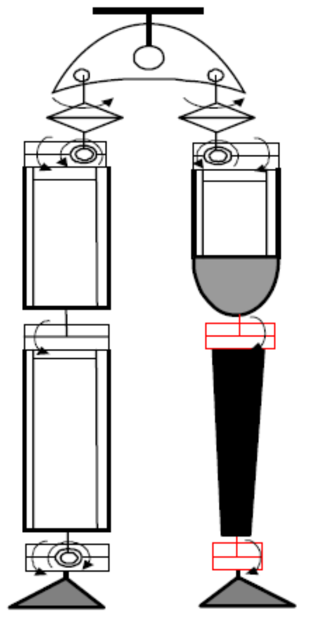

Fig. 2 Biped robot with heterogeneous legs

Overall structural design of the artificial leg

The main function of the artificial leg is to simulate normal human gait, which is the target of gait tracking for IBL. Therefore, personalisation of the artificial leg is particularly important. Currently, deep researches of humanoid robots have been carried out. Basic movements of human legs, including stable walking, going up and down stairs, turning and dancing, have been achieved. However, many problems still exist in the development of a humanoid robot: 1) Its walking gait is unnatural and is significantly different from that of a human leg; 2) Due to the limitations of the mechanism structure, the impact between the feet and the ground is large and the walking speed is slow; 3) Energy consumption and drive rigidity are large and hamper the realization of flexible joint movement. Based on an analysis about the physical structure and the basic movement of the human lower limbs, the structure of an artificial leg which is used for simulating a healthy human leg is designed in this paper. The overall structure of the artificial leg includes a knee joint mechanism and its drive mode.

Human leg bones include a hip bone, a femur, a patella, a fibula, a tibia and a tarsal bone, as shown in Fig. 3. The hip bones, which are composed of three skeletons each, are the pontes of upper and lower limbs. The lower leg bone consists of a tibia and a fibula. The tibia bears the weight and the fibula is only to stabilize the ankle joint. The contact surface between the femoral bottom and the tibial top is irregular. During flexion and extension activity of the knee joint, there is both rolling and sliding between the two contact surfaces. The outstanding feature of the knee joint is that its instantaneous centre of rotation (ICR) is not fixed and is similar to a “J” curve [2].

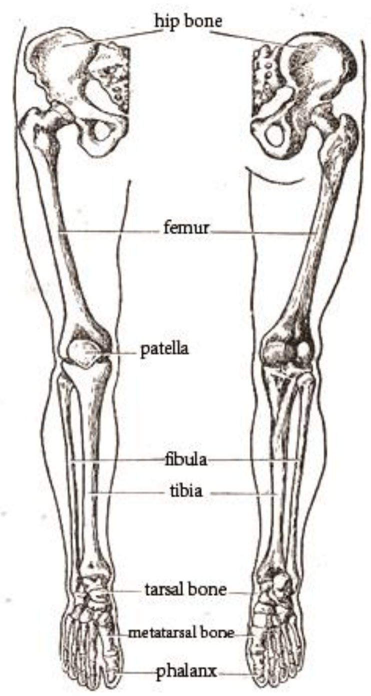

Fig. 3 Structure of human leg bones

As a part of the prosthetics experimental platform, the artificial leg is mainly used to simulate the natural walking of a human healthy leg and to provide a gait following object for intelligent prosthetics. Therefore, the artificial leg not only needs to achieve humanoid and steady walking, but also has to be highly consistent with human gait. A four-bar closed-chain knee mechanism [7], which has the advantages of the “J” curve of ICR, higher ground clearance and better stability, is adopted in the design of a knee joint. The human knee joint is driven by antagonistic muscles which can provide not only the driving force for precise position control, but also have good flexibility to absorb vibration and buffer impact. Currently, most joints of legs are driven by electric or hydraulic actuators, etc. The actuator of a common humanoid robot has obvious differences from that of a human. The pneumatic muscle actuator (PMA) has the advantages of light weight, simple structure, large output force, good flexibility and force-length characteristics that are similar to a human muscle, etc. In this paper, the knee joint is driven by a couple of PAM through an installed sprocket. In order to prevent axial movement of the sprocket, the latter is fixed by a shaft shoulder and a clasp on both sides separately. The virtual prototype of a knee joint driven by PMA is shown in Fig. 4.

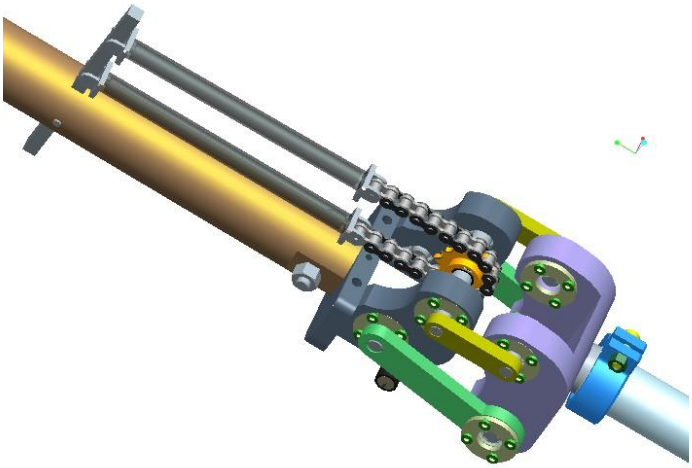

Fig. 4 Virtual prototype of a knee joint driven by PMA

In addition, in the process of structural design of an artificial leg, the normal structure size of a human leg should be fully considered. An adult man's basic data of China, which is shown in Table 1, is used as a reference. The dimensions of the bars are close to the normal structure size and the motion range of the joints is as similar to that of human joints as possible.

Table 1. Referenced human parameters

Item	**Value**
Height	1.76 m
Length of thigh	0.46 m
Length of shank	0.48 m
Height of foot	0.1 m
Width of foot	0.07 m
Length of foot	0.25 m
Distance from the center position of ankle joint to heel	0.055 m
Weight of thigh	7.725 kg, accounting for 10.3%
Weight of shank	3.225 kg, accounting for 4.3%
Weight of foot	1.125 kg, accounting for 1.5%
Normal pace	95~125 step/min
Step size	150~160 cm
Step width	5~10 cm
Stride length	75~83 cm
Gait cycle	0.45~0.6 s
Ratio of support phase	40% of gait cycle
Ratio of swing phase	60% of gait cycle
Extension angle range of ankle joint	flexor 20°, dorsiflexion 15°
Extension angle range of knee joint	full stretch, flexion 60°
Extension angle range of hip joint	anteflexion 30°, extension 10°

The whole structure of artificial muscles should be composed of a hip joint, a thigh bar, a four-bar mechanism, a shank bar, an ankle joint and an artificial foot. Since the paper mainly studies the walking of an artificial leg on a plane, its structure is simplified as follows: hip and ankle joints are reduced to one degree of freedom respectively. The virtual prototype and a schematic representation of the artificial leg are shown in Fig. 5 and Fig. 6 respectively.

Although a four-bar mechanism is used to simulate the movement of the knee joint, the swing between the connecting rods is not free. The four-bar mechanism has only one degree of freedom and should satisfy the following constraints:

$$-L_9^a e^{j(\theta_2^a-\alpha)} - L_3^a e^{j\theta_3^a} + L_{10}^a e^{j(\theta_5^a-\beta)} + L_4^a e^{j\theta_4^a} = 0 \tag{1}$$

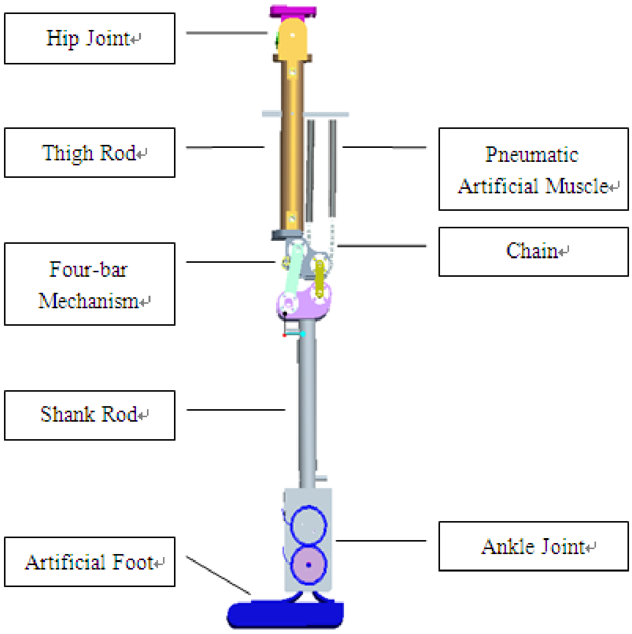

Fig. 5 Virtual prototype of an artificial leg

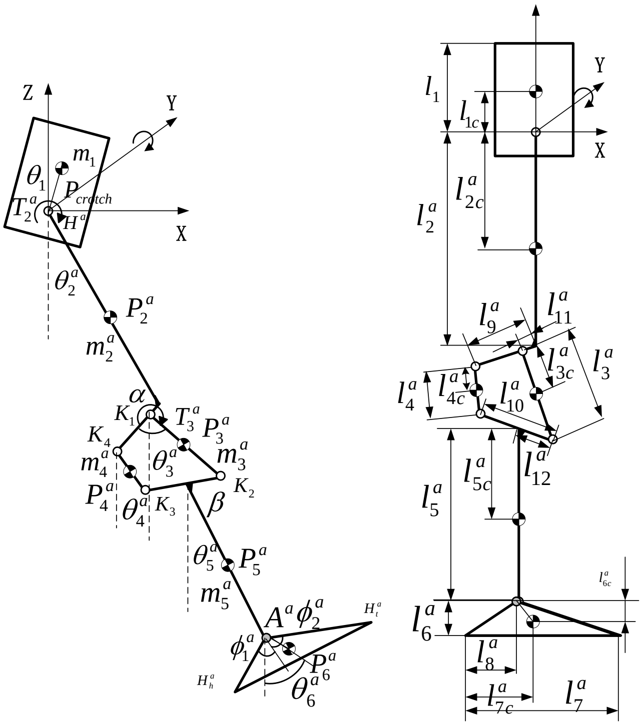

Fig. 6 Schematic representation of an artificial leg

Mathematical modeling of PAM

Due to the problem of material and structure, the relationship between the driving force, the inflation pressure and the contraction ratio is nonlinear. The characteristics of PAM cannot be described by an accurate mathematical model. The application difficulties of PAM mainly concentrate on establishing its accurate mathematical model.

At present, the commonly used static model of PMA is derived by Chou and Hannaford based on the principle of virtual work [9]. The formula can be written as follows:

$$F_0 = p\left[a(1-\varepsilon)^2 - b\right] \tag{2}$$

$$a = \frac{3\pi D_0^{\ 2}}{4\tan^2\theta_0},\ b = \frac{\pi D_0^{\ 2}}{4\sin^2\theta_0},\ \varepsilon = \frac{L_0 - L}{L_0} \tag{3}$$

where D_0 is the initial diameter of PAM; θ_0 is the initial angle between the mesh grid and the axis of PAM; L_0 and L are the initial length and the inflated length of PAM respectively; ε is the shrinkage rate of PAM; p is the internal relative pressure of PAM.

However, this mathematical model is simplified with some assumptions: 1) The shape of PAM is ideally cylindrical and unchangeable during a shrinkage process; 2) The elastic force of the rubber tube and the friction between the rubber tube and the mesh grid are ignored. Thus the position control of PAM using this mathematical model will lead to a large error in the process of practical application. Many researchers in China and abroad have improved this mathematical model by taking into consideration the practical application. To consider the effect of the muscle end hemispherical expansion to its contraction force during the actual contraction process the coefficient k is introduced. Caldwell et al. [3] think radian part of PAM end as variable cross-section muscles with continuous change to consider its effect on the contraction force. Compared with other models, this improved model has been proved to come closer to the actual characteristics of PAM by experiment. Yang et al. [8] at Huazhong University of Science and Technology have improved the mathematical model of PAM by putting forward PAM as a variable cross-section cylinder and considering the effect of the rubber elastic force during the shrinkage process. Considering the fluid damping of the high-speed gas flow and the rubber damping, He et al. [4] have simplified the damping force as a linear relationship of the strain rate and established a new mathematical model of PAM, which can be described as follows:

$$F = F_0 + F_f + F_z$$

where F_0 is the PAM contraction force of Chou ideal model; F_f is the friction force; F_z is the damping force.

Based on the mathematical model of PAM above, and considering the end deformation of PAM, the elastic deformation of the rubber tube and the friction between the rubber layer and the mesh grid, a static mathematical model of PAM is proposed in the paper, which can be described as follows:

$$F = k_0 p\left[a(1-k_1\varepsilon)^2 - b\right] - F_z \pm F_f \tag{4}$$

$$F_z = \pi D_0 L_0 t E (1-\varepsilon)^2 \left(\frac{1}{\sin\theta_0} - \frac{1}{\sin\theta}\right)\cos\theta_0 \tag{5}$$

$$\sin\theta = \sqrt{1-(1-\varepsilon)^2}\cos\theta_0 \tag{6}$$

where F_z is the damping force; k_0 and k_1 are the modifying factors in consideration of the PAM ends shape changing and length-diameter ratio; E is the elasticity modulus of the rubber tube; t is the wall thickness of the rubber tube; θ is the angle between the braided line and the PAM axis; F_f is the friction between the rubber tube and the mesh grid. Supposing that the static friction is constant, the direction of F_f changes according to the stretching and shrinkage of PAM.

Mechanical model of a joint driven by PAM

Since single PAM can only provide one-way force and the knee joint of the artificial leg needs to be driven by torque, the PAM is usually used in pairs. In this paper, two PAM which are connected by a sprocket and a chain are adopted. By inflating and deflating, contractility of PAM will be produced and will drive the sprocket to rotate. Then the load and the bars which are connected with the sprocket will rotate. The working principle of the joint driven by PAM is shown in Fig. 7. The initial pressure of PAM should be given to ensure that the two pneumatic artificial muscles have the same internal pressure and shrinkage.

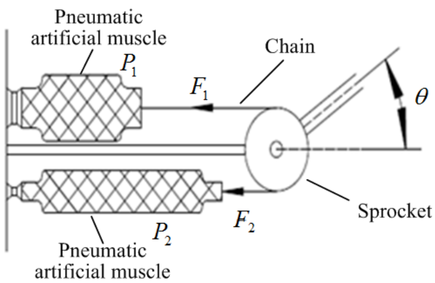

Fig. 7 Principle of the joints driven by PAM

The initial angle of the joint is zero and the initial shrinkage rate of PAM is described as ε_0 under precompression. When the two pneumatic artificial muscles are inflated with different pressure, the whole joint is in equilibrium and the joint angle of rotation is described as θ. At this moment, the shrinkage rate of both pneumatic artificial muscles can be described as follows:

$$\begin{cases} \varepsilon_1 = \varepsilon_0 + \dfrac{r\theta}{L_0} \\ \varepsilon_2 = \varepsilon_0 - \dfrac{r\theta}{L_0} \end{cases} \tag{7}$$

The torque provided by PAM can be calculated as follows:

$$T = r(F_1 - F_2) \tag{8}$$

Input Eqs. (4), (5), (6) into (7), the following relationship can be obtained:

$$T = ra\left[k_0 p_1 (1 - k_1 \varepsilon_0 - k_1 \frac{r\theta}{L_0})^2 - k_0 p_2 (1 - k_1 \varepsilon_0 + k_1 \frac{r\theta}{L_0})^2\right] + rb(k_0 p_2 - k_0 p_1) + T_z + T_f \qquad (9)$$

where r is the radius of the sprocket; θ is the rotation angle of the drive shaft; p_1 and p_2 are the internal pressures of both PAM after inflation and deflation; T_f is the torque produced by the PAM friction.

Control simulation based on a control algorithm

Conventional PID control is one of the most widely used control strategies in the process of industry control currently. Based on the feedback principle, it mainly includes proportional, integral and differential control. This method has a number of advantages, such as a simple principle, usability, strong adaptability and robustness. According to statistics, more than 95% of the control loops of industrial process have PID structure and many advanced controls are based on PID control. The PID control law can be described as follows:

$$u(t) = K_p (e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d \frac{de(t)}{dt}) \qquad (10)$$

Since the structure of artificial legs with a closed chain constraint is more complex, it is difficult to establish a precise mathematical model. In the paper, the virtual prototype of an artificial leg is established using software Pro/E and is imported into MATLAB/Simulink using interface between ADAMS/Controls module and MATLAB/Simulink module. Then the control simulation based on a PID control algorithm is carried out to verify the rationality of the mechanism design. The block diagram of the combined control simulation is shown in Fig. 8.

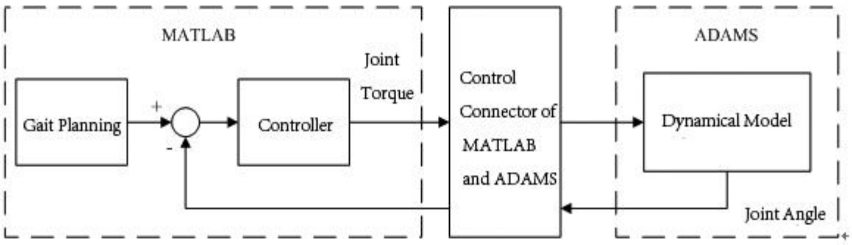

Fig. 8 Block diagram of combined control simulation

The gait tracking goals of an artificial leg to a normal human leg are a natural human gait of the hip joint and the knee joint. The ideal gait data of the hip and the knee joints is derived from APAS software with an absolute coordinate system. The sampling interval is 0.005 s and the simulation time is 0.25 s. After data processing using MATLAB, the ideal data curves of hip and knee joints are obtained as shown in Fig. 9 and Fig. 10.

Based on the PID control algorithm, the controller simulation module is built in MATLAB/Simulink. MATLAB/Simulink adopts the modular modeling method and takes an ant_test module which is packaged into MATLAB by ADAMS/Controls as a control object. The main structure of the module ant_test is shown in Fig. 11.

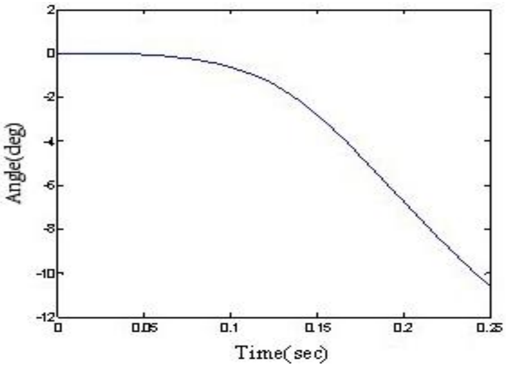

Fig. 9 Ideal data curve of hip joint

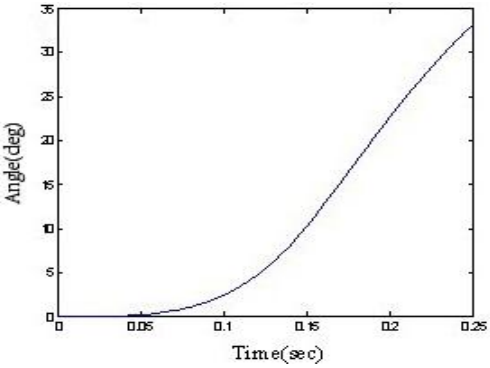

Fig. 10 Ideal data curve of knee joint

Here T_1 and T_2 are the input of the control system, namely the driving torque of the hip and the knee joints; M_1 and M_2 are the output of the control system, namely the rotation angle of the hip and the knee joints.

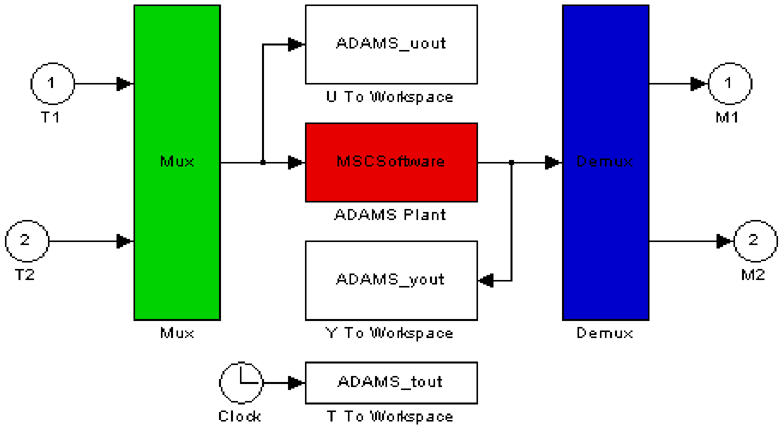

Fig. 11 Control object module generated by ADAMS

The PID controller of the virtual prototype model of the artificial leg is built using MATLAB/Simulink which is shown in Fig. 12. The feedback signal which continually corrects the input of the control module is the error between the ideal value and the actual output.

The proportional, integral and differential coefficients of the PID controller are continually adjusted by the method of trial and error. The relative angle tracking of the hip joint is illustrated in Fig. 13, and the tracking error is shown in Fig. 14.

The relative angle tracking of the knee joint is illustrated in Fig. 15, and the tracking error is shown in Fig. 16. The simulation results indicate that the artificial leg can simulate the normal walking gait of a human, precisely based on the PID control algorithm.

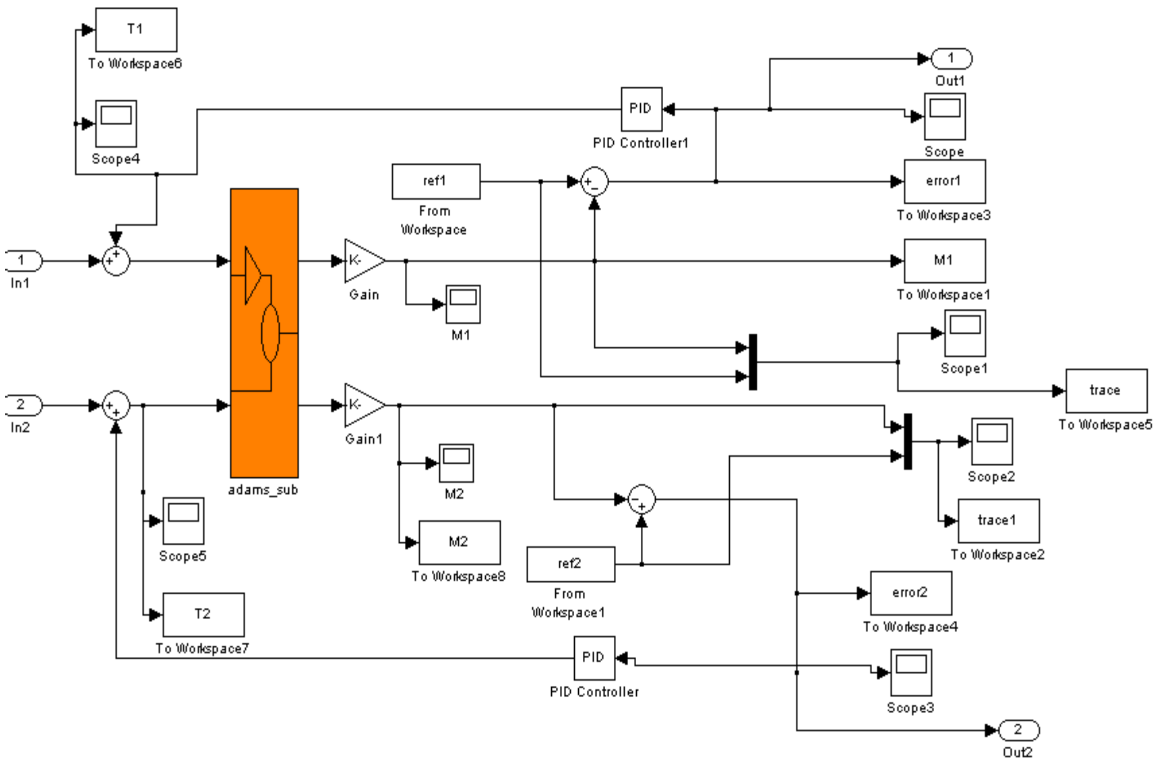

Fig. 12 Block diagram of the PID control model

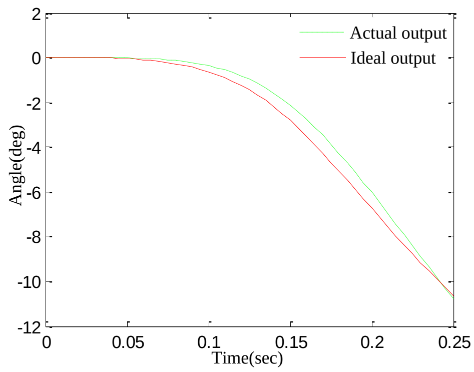

Fig. 13 Tracking curve of the hip joint

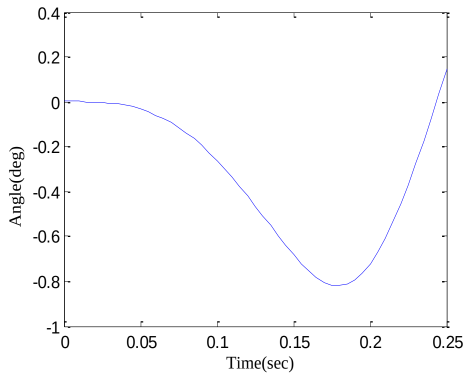

Fig. 14 Tracking error of the hip joint

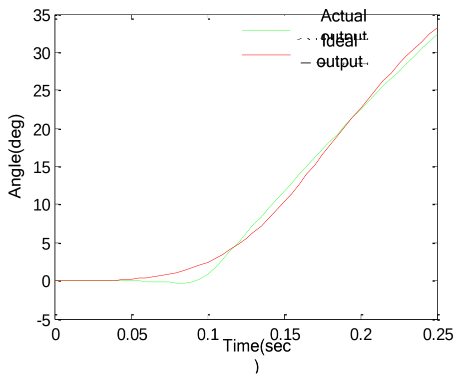

Fig. 15 Tracking curve of the knee joint

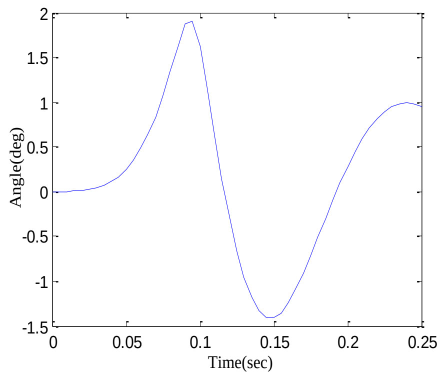

Fig. 16 Tracking error of the knee joint

Conclusion

Intelligent bionic legs brings about great social and economic benefits. The biped robot with heterogeneous legs is an ideal test-bed for an intelligent bionic leg. The structure and control model of an artificial leg with a four-bar mechanism and a pneumatic muscle actuator are similar to that of a human's knee with muscle and ligament. The control simulation of an artificial leg based on the PID control algorithm indicates that the artificial leg can simulate the normal movement of a human healthy leg well.

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