Development and Physical Control Research on Prototype Artificial Leg

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Abstract: *To provide an ideal platform for research on intelligent bionic leg (IBL), this paper proposes a model of a biped robot with heterogeneous legs (BRHL). A prototype of an artificial leg is developed based on biological structure and motion principle analysis of human lower extremities. With regard to the driving sources, servomotors are chosen for the hip joint and ankle joint, while pneumatic muscle actuators (PMAs) are chosen for the knee joint. The control system of the bionic artificial leg is designed and a physical experimental platform is established. The physical control experiments are done based on proportional-integral-derivative (PID) control strategy. The experimental results show that such a system can realize the expected goals.*

Keywords: *Artificial leg, Physical control, Knee joint, Pneumatic muscle actuators.*

Introduction

Data from the Second National Sample Survey on Disability in 2006 [9] shows that there are 2.26 million amputees, 70% of which are lower extremity amputees. The intelligent bionic leg (IBL) [7, 8] which is an advanced intelligent prosthesis [3] is the ideal way to compensate for walking functions of amputated lower extremities. During the development of IBL, many various and repeated walking tests by amputees with IBL are necessary. However, IBL tests are exhausting to the amputees. It is not only costly but also painful to the subjects involved and could lead to unintended harm to the test amputees. Furthermore, personal factors of the amputees often lead to certain interference to the experiment results. To provide an ideal testbed for the development of an IBL, a new pattern humanoid robot – biped robot with heterogeneous legs (BRHL) [1] was proposed, as shown in Fig. 1. BRHL consists of two legs: one is an artificial leg and the other is a bionic leg which is composed of hip joints of an artificial leg and an IBL. The robot body and artificial leg corresponds to amputees and the bionic leg corresponds to the intelligent prosthesis used by amputees. The artificial leg mainly simulates the human healthy leg to produce normal gait for the test of IBL.

Compared to other actuators, the pneumatic muscle actuator (PMA) [6] has advantages of a relatively simple structure, light weight, low cost, higher output under the same weight, and similar properties to biological muscle. The PMA has been widely used in the field of rehabilitation medicine. To ensure humanoid characteristics in the artificial leg, the advantages of humanoid robots and PMAs are combined in this research. Servomotors are chosen for the hip joint and ankle joint, while PMAs are chosen for the knee joint. Three-dimensional modeling, interference checking and motion analysis are done based on software Pro/E and a prototype of the artificial leg is developed. With programmable multi-axes controller (PMAC) motion controllers as the core, the entire control system of the artificial leg is designed, and the experimental platform of motion control is established. The experimental study of motion control on artificial leg is completed based on control strategy of industrially mature proportional-integral-derivative (PID). The virtual prototype and the prototype of the artificial leg developed by the present research group are shown in Fig. 2.

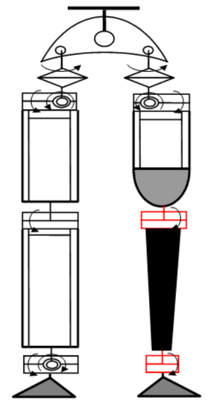


Fig. 1 Biped robot with heterogeneous legs

a) virtual prototype b) prototype

Fig. 2 The virtual prototype and the prototype of the artificial leg

Mechanical design of artificial leg

According to research on biological structure and motion principles [2], the motion of human lower extremities is realized by a coordinated motion of hip, knee and ankle joints, whose degrees of freedom are respectively 3, 1 and 2. Muscles, which are dominated by the nervous system, are the power source of each joint system. Muscles draw corresponding bones to complete corresponding motion of joint. Based on the characteristics of a human leg, and combined with straight gaits of human walking, this paper respectively simplifies the structure model of hip and ankle joints into a revolute joint with only one degree of freedom (DOF). Since the motion trajectory of the knee joint is more complicated, the four-bar closed-chain multi-axis knee mechanism [4] is adopted by the knee joint of the artificial leg to guarantee humanoid characteristics.

Mechanical design of hip and ankle joints

According to human biological data, the hip and ankle joint with one DOF are designed respectively. Since both joints are simplified into a revolute joint with one DOF, this research adopts motor drivers, which are the most direct and effective method. The hip joint can swing under the action of motor input torque to achieve flexion and extension movement. In practical control, the upper part of the hip joint needs to be fixed to a steel panel, while the motor cannot be fixed in this research. Thus the hip joint is controlled to rotate under the principle of motor axis positioning and rotation of motor body driven by joint. Under the effect of motor input torque, the ankle joint exhibits dorsiflexion and plantar flexion. Since the length of the motor plus reducer is longer, the motor and the reducer cannot be coaxial with the ankle. Therefore, in this paper we adopt a gear drive, which has a higher transverse compact in the ankle and an enhanced driving precision.

Compared to direct-current servomotors, alternating-current ones have larger torques, higher efficiency, better torque characteristics, lower maintenance cost, and an extended life cycle under the same volume. Since the design purpose of the artificial leg is to simulate the natural gait of a human healthy leg, the requirements for torque characteristics, efficiency and life cycle of motor are higher. Compared with IBL, the artificial leg with a greater weight is active and needs a motor with larger torques. With all factors considered, in this research we finally choose an alternating-current servomotor as the driving device. Through calculation, the maximum torques needed for hip and ankle joints are 45.85 Nm and 8.6 Nm respectively. The driving devices chosen in this paper are shown as follows.

The driving device of the hip joint: SGMJV-04ADE6E (alternating-current servomotor) and SGDV-R90A01B002000 (servo driver) with rated power of 400 W and a rated torque of 1.27 Nm; IB060L2-32-P2-S2 (harmonic reducer) with the reduction ratio of 32 and a rated torque of 50 Nm.

The driving device of the ankle joint: SGMJV-01ADE6E (alternating-current servomotor) and SGDV-2R8A01B (servo driver) with rated power of 100 W and a rated torque of 0.31 Nm; IB060L2-12-P2-S2 (harmonic reducer) with a reduction ratio of 12 and rated torque of 40 Nm.

Mechanical design of knee joint

The human knee joint is mainly composed of the femur, tibia and patella. The contact surface between femoral bottom and tibial top is irregular. There are both rolling and sliding interactions between the two contact surfaces. The outstanding feature of knee joint is that its instantaneous centre of rotation (ICR) is not fixed but a "J" curve [5] that changes greatly. The knee joint of the artificial leg adopts a four-bar closed-chain multi-axis knee mechanism to simulate the human bone structure. Also, PMA, which resembles the property of biological muscle, is adopted as the driving device. According to the construction of a normal human leg, and considering the length and tension of artificial muscle, the paper chooses PMA of the MAS series from FESTO, a German corporation. For human beings, the flexion and extension of knee joints are cooperatively controlled by anterior and posterior muscle groups in both sides of the thigh. Combined with the driving features and arrangements of muscles in human lower extremities, knee joints are driven by the form of two PMA pulling each other. To obtain a bigger output torque for the benefit of enough motion scope when knee joints bear load, chain drive is adopted in this research. Although the chain drive will increase the structure size of the artificial leg, it has advantages of a simple structure, strong carrying capacity, high transmission precision, etc. The principle of chain drive is shown in Fig. 3 as follows.

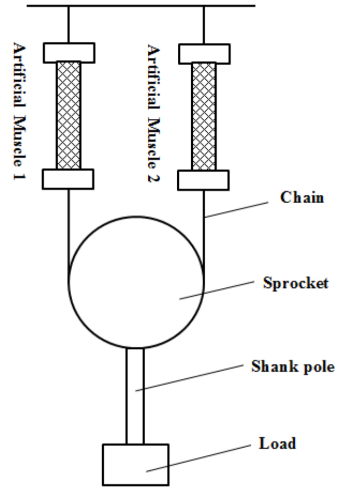


Fig. 3 Drive mode of PMA in knee joint

According to the drive mode of the knee joint in Fig. 3, the load and the shank can together be seen as an equable slender bar with a length of l and the quality of m. By means of mechanical transmission of the sprocket and chain on the active axis of the four-bar mechanism, the input force of PMA is transferred to the knee joint. Supposing the slender bar is equable, the initial angle of the joint is zero, the initial length of the PMA is L_0, and the radius of the sprocket is r_w, the two PMAs produce an equal shrinking tension when being inflated with the same amount of air, namely $F_1 = F_2$. By inflating one PMA while deflating the other one at the same time, the output force of the two PMA changes. Then, a difference of the tensile force, namely $F_1 = F_2$, is generated, under which the sprocket rotates to a certain angle.

The following relationship can be derived from the torque balance equation, as shown in Eq. (1) and Eq. (2).

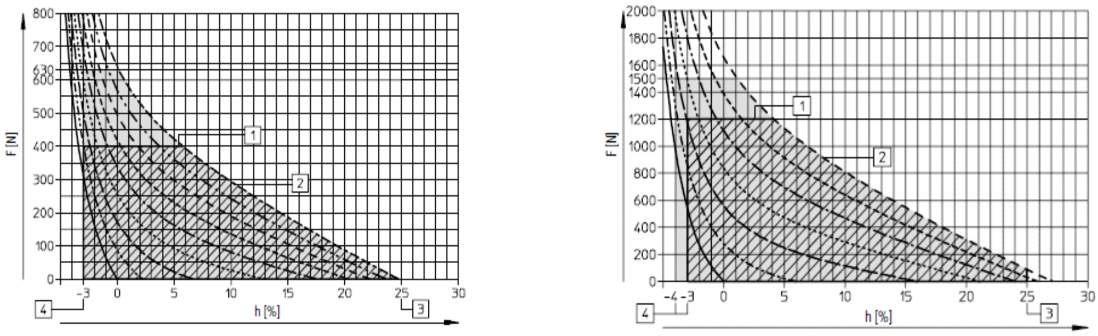
$$(F_1 - F_2) \cdot r_w = 1/2 \cdot m \cdot g \cdot l \cdot \sin\theta \quad (1)$$

$$(F_1 - F_2) = 1/(2r_w) \cdot m \cdot g \cdot l \cdot \sin\theta \quad (2)$$

According to the structure of the human body and mass distribution, an initial data for parameters m, l, r_w is obtained (g is the gravitational acceleration).The theoretical maximum rotational range of the knee joint is between 0~115°. When $\theta = 90°$, the theoretical load torque reaches the maximum. By inserting the initial data into the Eq. (2), the theoretical maximum difference of the tensile force is obtained as follows:

$$F_1 - F_2 \leq 897.5 \text{ N} \quad (3)$$

For the FESTO-MAS series of PMA with a diameter of 10 mm and that of 20 mm, the relationship between the output force, the working pressure and the shrinkage rate is shown in Fig. 4. There “1” denotes the maximum output force, “2” denotes the maximum working pressure, “3” denotes the maximum shrinkage rate, and “4” denotes the maximum pre-tightening. As shown in Fig. 4, the maximum output forces of the two PMA are 400 N and 1200 N respectively. Since the latter can meet the maximum torque needed for the knee joint, thus PMA with a diameter of 20 mm is chosen in this research.



a) PMA with the diameter of 10 mm b) PMA with the diameter of 20 mm

Fig. 4 Relationship between the output torque, working pressure and shrinkage rate of PMA

The longer is the length of the PMA, the greater its maximum shrinkage rate. Taking into account the life and security, the maximum shrinkage rate of the PAM is 25%. Limited to the mechanical structure of the artificial leg, the chosen PMA should not be longer than 110 mm. In order to determine the length of the PMA, the contraction length ΔL of the PMA when the knee joint bends to the maximal rotational angle should be first determined according to Eq. (4).

$$\Delta L = 2\pi r_w \frac{\theta}{360°}. \qquad (4)$$

To make the length of PMA small enough, the radius of the sprocket should be as small as possible. Based on an overall analysis of the size of the four-bar mechanism, the force condition and motion stability of the chain, a chain of 05B type is chosen in this research, where the diameter of its roller is 5 mm, the number of teeth is 15, and the diameter of reference circle is 38.478 mm.

By inserting $\theta = 115°$, and $2r_w = 38.478$ into Eq. (4), it can be obtained that $\Delta L \approx 40$ mm. Since the maximum shrinkage rate that PMA can utilize is about 25%, the needed length of PMA is about 160 mm, which is much larger than 110 mm. For the purpose of using a shorter PMA, while at the same time, the maximum rotational angle can be achieved, a gear acceleration mechanism with a speed increasing ratio of 2.5 is added between the sprocket and the four-bar mechanism, where the module of the gear is 1.5, the number of teeth of the two gears is respectively 18 and 44. In this way, the accuracy and stability of the mechanism transmission is guaranteed. MAS-20-100N-AA-MC-O-ER-EG (PMA) is chosen as the driving devices of the knee joint in this research, where the diameter of the rubber hose is 20 mm, the length is 100 mm, the maximum tension is 1200 N, and the maximum shrinkage rate is 25%.

In summary, the developed knee joint of the artificial leg is shown in Fig. 5.

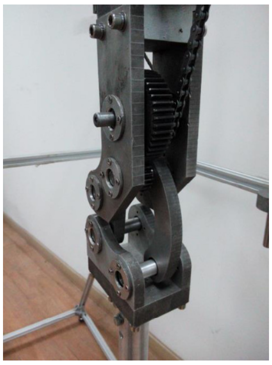


Fig. 5 Knee joint of artificial leg

Experiment research of artificial leg movement control

Design of the control system of the artificial leg

The hip and the ankle joints of the artificial leg have fixed-axis rotation with one degree of freedom, and the control of joint gaits is converted into that of joint angles. Since the trajectory control of joints has high accuracy requirements on motors, the speed control mode of the servomotor is adopted. Under such a mode, a control input of an analog signal with ± 10 V is added to the servo driver, which is compared to position feedback signal of the absolute position encoder of the servomotor. Thus, a closed servo-control system is constituted.

The knee joint of the artificial leg rotates by the way of two PMAs pulling each other, and has its motion range broadened by adding a gear acceleration mechanism. In the control experiment, the expected gait signal and the feedback signal of the knee incremental encoder are contrasted. Then, after the processing of control algorithms, Pulse Width Modulation (PWM) control signals of u_1 and u_2 with an adjustable duty cycle are sent by the motion control card of the PMAC. These two signals control each group of the two high-speed switching valves, respectively. Thus the extension and shrinkage of the PMA are manipulated to finally achieve the goal of controlling the rotation angle of knee joint.

By integrating the control system of the three joints and rationally distributing the control axis ports of the PMAC, an overall control scheme of the artificial leg is established in Fig. 6.

Experimental platform establishment of the artificial leg

The experimental platform established includes output circuits of the Clipper card; junction circuits of the servo driver; contracting brake circuits of the motor based on an electric relay; junction circuits of the high-speed switching valve and a pneumatic circuit with a cylinder as the power source. After the electricity supply in every circuit is modulated to a normal state, the software of the PEWIN32-Pro2 Suite is installed in the industrial control computer, thus a software development environment is built up. In the control system of the lower computer, the PWM pulse-modulated signal is outputted with the Clipper card of the PMAC as the core, while in the upper computer, the industrial control computer is connected to the Clipper card through Ethernet, and information interactions are completed. The real-time control of the experimental platform, and the collection and processing of experimental data are realized through the upper computer.

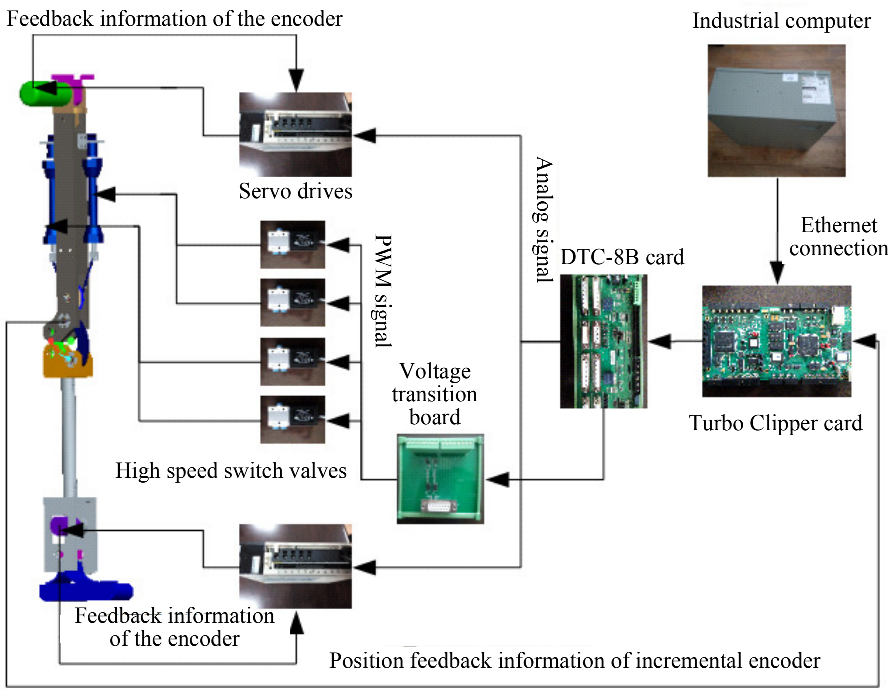


Fig. 6 Overall control scheme of the artificial leg

In the software, different profiles are compiled according to different control circuits. Axis 1 and Axis 2 of the Clipper card are set as the output axis controlled by the analog quantity of the servomotors to control the hip and ankle joints. Axis 3 is set as the EQ axis to output PWM pulse-modulated signal for the on-off control of the high-speed switching valves. The default three-phase power supplies, pulse output and position model are set as the single-phase power supply, analog output and velocity model.

The established experimental platform of the artificial leg is shown in Fig. 7.

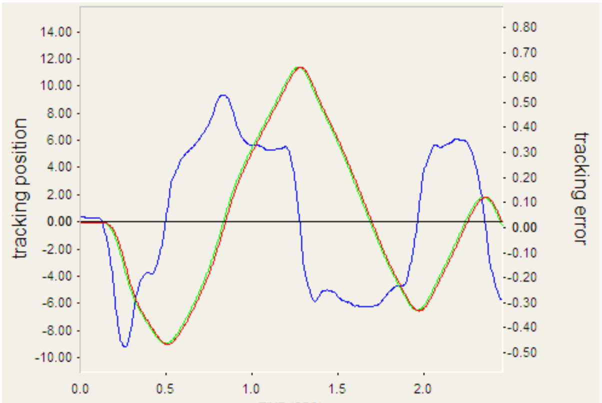
a) control object b) control devices

Fig. 7 Experimental platform of the artificial leg

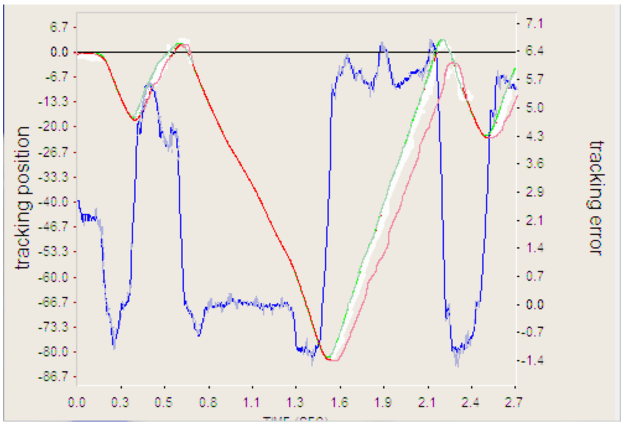
Gait tracking experiment of the artificial leg

Using normal human gait data gained from APAS software from Ariel Dynamics Co., a Gait tracking experiment of the artificial leg is done based on the PID control strategy. The gait tracking results of the hip, knee and ankle joints are shown in Fig. 8.

a) gait tracking of hip joint



b) gait tracking of ankle joint



c) gait tracking of knee joint

Fig. 8 Gait tracking of hip, knee and ankle joints

In the experiment, the red line denotes the practical tracking curves (Left-Vertical), the green one denotes the ideal curve (Left-Vertical), and the blue one denotes the tracking error (Right-Vertical) as measured in degrees. From Fig. 8, it can be seen that the tracking effect of each joint is favorable. The maximally steady-state error of the knee joint is 5~6° and that of the hip and ankle joint is 0.5~0.6°, both of which are acceptable. In the starting time and the reversing time, each error has a great sudden change, which is mainly because of the certain inertia of the mechanical structure below the knee joint of the artificial leg. A relatively obvious hysteresis and buffeting arise during the process of steady movement of the knee joint, which is related to the pressure instability of the pneumatic circuit. The parameters of the PID controller are obtained through the trial-and-error method, which means that it has a great influence on the subtle treatment on tracking, in spite of the fact that a better gait tracking trend can be achieved.

Conclusion

A prototype of an artificial leg with relatively good humanoid characteristics is developed based on biological structure and motion principle analysis of human lower extremities. A control experimental platform of the artificial leg is built up, in which gait tracking experiments of all joints of the artificial leg are carried out based on PID control strategy. The results show that the control system of the artificial leg is rationally designed and has reached the expected goals effectively.

Acknowledgements

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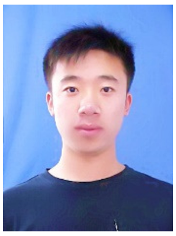

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