Inverse Dynamic Compound Control for Intelligent Artificial Leg Based on PD-CMAC

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Abstract: - Traditional mathematic model is not suitable for actual control, because the knee torque of intelligent artificial leg (IAL) is indirectly caused by the nonlinear damping. An inverse dynamic compound control for intelligent artificial leg was studied. A dynamics model of hydraulic IAL with the nonlinear damper control parameters and hip torque was set up, and an inverse dynamic compound controller based on PD-CMAC for tracking the knee swing was designed. The simulation results show that an arbitrary trajectory such as a desired walking pattern can be tracked in less than 0.5 seconds, which proves that the controller meets real time and precision demanded.

Key-Words: - intelligent artificial leg, compound control, dynamic model, cerebellar model articulation controller

1 Introduction

The biomechanical system consisting of skeleton and muscle can strongly adapt to walking. It is important to study intelligent artificial leg (IAL) with the feature of knee adaptability being critical in biomechanical system. The IAL can improve the safety of artificial leg and the quality of life of amputee. Intelligent artificial leg system (IALs) is defined as a complex system due to the parameter uncertainties to terrain caused by patient wearing and the nonlinearity in model. So it is necessary to propose the intelligent control methods for IAL.

While, the intelligent control of IAL isn't enough. Furthermore, most control thoeries studied for IAL focus on fuzzy control [1], BP neural network control [2, 3] and expert control [4]. The advance intelligent multiple control methods, such as neural network adaptive control, haven't been applied in reality. In [1], Feedback-error learning (FEL) neural network was developed for control of a powered trans-femoral prosthesis. The FEL control method based on BP neural network (BPNN) was presented, but the BPNN controller can't meet real time demand. This paper presents PD/Fuzzy-CMAC adaptive control algorithm which can keep the symmetry of IAL swing. The algorithm can ensure the system stability and real-time performance.

2 Features of Normal Gait and Requirements of IAL

In locomotion, body motion control is processed by the neuro–muscular subsystem and actuated over the body segments (skeleton) around its joints by the musculo–skeletal subsystem. During gait the musculo–skeletal system continuously changes its segmental configuration in a rather complex way. The motions of the body segments serve for locomotion and maintaining stability. During one gait cycle, the leg configuration performs two different phases, twice. One is the single limb support phase (SLS) when one leg is swinging (almost freely) forward and the other leg supports the body. The second is the double limb support phase (DLS) when the two legs stand on the ground and both support the body. The relative timing between the two phases is described in Fig. 1[5].

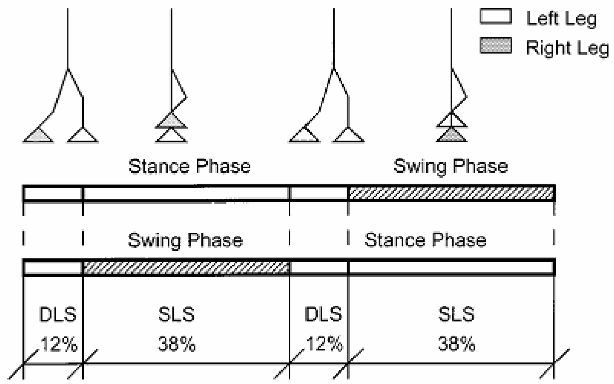


Fig.1. Time sharing between single and double limb support

At the end of single support phase, the biggest vertical loading condition comes into being. Then the knee starts to bend to be ready for swing phase. Therefore, at this time, the flexion resistance should be the minimum. At the start swing phase, the knee joint has flexed to 30°. The maximum flexion angle is from 55° to 65°. During SLS the segmental structure is that of an open link chain, and during DLS both legs are on the ground applying the motion constraints of a closed link chain. During one gait cycle in average walking speed, each SLS phase lasts about 38% of the cycle period, and each DLS lasts about 12%. The period of DLS phase is decreased as gait speed is increased. So the movement of knee joint would be a short period of time. IAL should start to move with the minimum flexion resistance, and be adaptable to gait velocity.

The above knee artificial leg is fixed under the amputees' hip, and the control system must match with biomechanical system of amputees [5, 6, 7]. Commonly, the ideal AKP artificial leg meets the requirements as follows [8, 9, 10].

1) Have sufficient weight to support the stability and security.
2) Has tripped automatically lock the ability to bend.
3) Throughout the gait cycle can sit, stand, downstairs / downhill walking, and other gaits.
4) The ability in response to instantaneous changes.
5) Able to adapt to different amputee personalized configuration requirements, no need for training in implementation of adaptive control. At heel contact the ability to absorb ground impact.

3 Design of PD-CMAC Based on IAL

3.1 Controller Design of PD-CMAC

CMAC (Cerebellar Model Articulation Controller) is an adaptive control network, with fast convergence speed, higher accuracy, and better real-time [11, 12]. CMAC has a wide range of current forms of control, such as CMAC direct inverse dynamic control, CMAC feed forward control, CMAC feedback control. In this paper, the CMAC and PD controller of a direct inverse dynamic feed forward and feedback control is designed [13, 14]. The control features is:

1) CMAC neural network controller is implemented by the feed forward control, and it is charged with implementation of the inverse dynamic model of the object.
2) Conventional feedback control is implemented by the feedback control, and it is ensure the stability and disturbance suppression of system.

For the legs to follow a healthy signal control system of the GF-IPL, the design of the PD-based neural network controller (CMAC) supervisory control model (Fig. 2). The output signals are obtained by cerebellar network feedback control through the PD controller and the input signals $X\left(\theta,\dot{\theta},\ddot{\theta}\right)$ are set for online training.

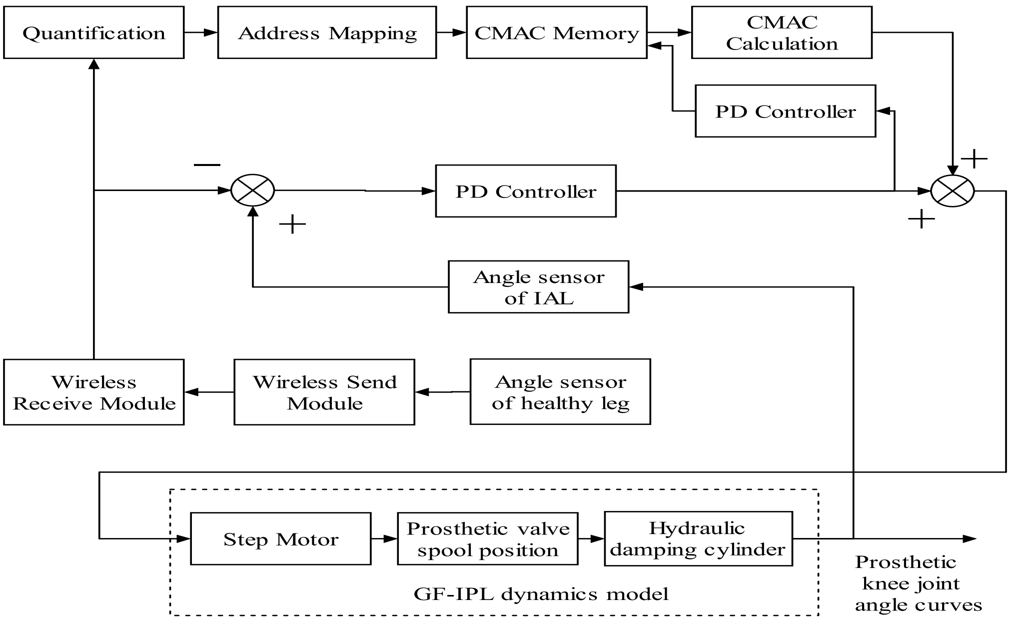


Fig. 2. PD-CMAC control model of GF-IPL system

3.2 PD-CMAC Learning Algorithm

CMAC has used the learning algorithm instructor. At the end of each control cycle, the corresponding CMAC output $u_n(k)$ is calculated. Then the total control input $u(k)$ is compared with $u_n(k)$, and it can adjust the weight of the amendment into the learning process [15, 16]. The purpose of study is to make the difference smallest between the control input and the output of CMAC. Adjust the target for the CMAC by

$$E(k)=\frac{1}{2}(u_n(k)-u(k))^2\cdot\frac{1}{c} \quad (1)$$

$$\Delta w(k)=-\eta\frac{\partial E(k)}{\partial w}=\eta\frac{u(k)-u_n(k)}{c}a_i=\eta\frac{u_p(k)}{c}a_i \quad (2)$$

$$w(k)=w(k-1)+\Delta w(k)+\alpha(w(k)-w(k-1)) \quad (3)$$

Where η is network learning rate, and $\eta\in(0,1)$. α is inertial and $\alpha\in(0,1)$.

At the beginning of the system run-time, let $w=0$, then $u_n=0$, $u=u_n$. At this point the system is controlled by the conventional controller. Through the study of the CMAC, the output of PID controller gradually become to zero, and the output $u_n(k)$ of CMAC control gradually converge to the total output $u(k)$.

4 Dynamics Model of Artificial Leg

In order to simulate or validate the proposed control method, a mathematics model has been set up using IAL as control object. Inverse problem of traditional dynamics can be formulated as: Given motion path, speed and acceleration of each point, it is necessary to provide generalized driving forces of active joint with time or translation changing for solution of drive element. To executive trajectory tracking control, joint torque of hip, knee and ankle can be obtained only using dynamics parameter of thigh to resolve directly reverse solution of dynamics equation. However, joint torque parameters using this method couldn't meet the control need of actual artificial leg, which would interfere with the joint torque of thigh gait, especially for knee joint torque which usually was controlled by nonlinear damping indirect control. Controlling output using micro-processor couldn't use the calculation results of this mathematical model to implement track of torque. So a human-machine dynamics model was set up using parameter of nonlinear damping indirect control and torque of hip joint based on IAL motion system of two rigid-bodies (Fig. 3). To simulate easily using Matlab software, a swing dynamics equation of artificial leg was derived using matrix formulation as equation 4 shows. The dynamics model of IAL can be expressed by

$$\mathbf{D}(\theta)\ddot{\theta}+\mathbf{C}(\theta,\dot{\theta})\dot{\theta}+\mathbf{G}(\theta)=\mathbf{\Gamma} \tag{4}$$

Where

$$\mathbf{D}(\theta)=\begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}$$

$$\mathbf{C}(\theta,\dot{\theta})=\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$

$$\mathbf{G}(\theta)=\begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$

$$\mathbf{\Gamma}=\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

$$\theta=\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

$$D_{11}=I_1+I_2+m_1 l_{G_1}^2+m_2 l_{G_2}^2+2m_2 l_1 l_{G_2}\cos(\theta_2)$$

$$D_{12}=D_{21}=-I_2-m_2 l_{G_2}^2-m_2 l_1 l_{G_2}\cos(\theta_2)$$

$$D_{22}=I_2+m_2 l_{G2}^2$$

$$C_{11}=-m_2 l_1 l_{G2}\dot{\theta}_2\sin(\theta_2)$$

$$C_{12}=m_2 l_1 l_{G_2}\left(-\dot{\theta}_1+\dot{\theta}_2\right)\sin(\theta_2)-\frac{c_1}{X^2}\dot{\theta}_2$$

$$C_{21}=m_2 l_1 l_{G_2}\dot{\theta}_1\sin(\theta_2)$$

$$C_{22}=\frac{c_1}{X^2}\dot{\theta}_2$$

$$G_1=-m_1 g l_{G_1}\sin(\theta_1)-m_2 g l_1\sin(\theta_1)$$
$$\quad -m_2 g l_{G_2}\sin(\theta_1-\theta_2)-c_2\theta_2$$

$$G_2=m_2 g l_{G_2}\sin(\theta_1-\theta_2)+c_2\theta_2$$

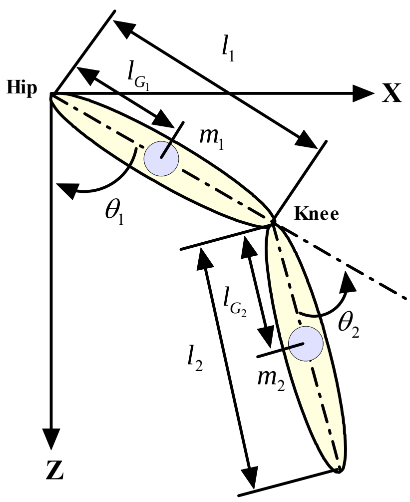


Fig. 3. Two rigid-bodies model of IAL

In Eq. 4, m_1, m_2 is quality of thigh, l_1, l_2 is length of thigh, l_{c1}, l_{c2} is position of mass center, θ_1, θ_2 is angle of thigh and leg, I_1, I_2 is moment inertial of center of mass of thigh and leg, M_1 is active torque of thigh and leg, M_1 is hydraulic cylinder resistance moment of knee gait, C_1 and C_2 is damping constant derived from nonlinear damping constant**,** Y is position of damp pin valve, respectively.

5 Compound Simulation of CMAC/PD

5.1 Settings for Simulation Parameters

In this paper, trajectory tracking for knee joint swing of IAL is studied based on compound control system between PD and CMAC control strategy. In Fig.1, when the integral parameters of PID controller are set to zero, we can have $C_1=0.346\left(\mathrm{N}\cdot m^4\right)$ and $C_2=1.76\left(N\cdot m\right)$. Where, $C_i\left(i=1,2\right)$ are parameters related to damp torque of knee joint.

The objective curves are sin functions respectively. The rotation motions of coax joint and knee joint are periodic trajectories, and they can be expressed by approximately half of sin periodic trajectories during stance phase. Moreover, this paper only researches tracking control effect of PD-CMAC controller to IAL. So sin curves are regarded as two input objective parameters.

In simulation experiments, the parameters of dynamics model are listed in Table 1.

5.2 Simulation Results

In order to study the control effect and robustness of GF-IPL system by PD-CMAC, some simulations are presented under different objective curves (frequency, amplitude) and mass. When the objective curve of coax joint is $\theta_1=\sin(\pi t)$ and the objective curve of knee joint is $\theta_2=\sin(\pi t)$, the simulation results are showed in Fig. 4 to Fig. 7. Where, Fig. 4 is the tracking trajectory of knee joint θ_2, Fig. 5 is the

Table 1. Simulation parameters of IAL model

Symbol	m_1	m_2	l_1	l_2	l_{G2}	ln	Δl
Unit	kg	kg	m	m	m	m	m
Value	3.72	8.05	0.435	0.412	0.19	0.03	0.02
Symbol	J_1	J_2	G	k	l_{G1}	ρ	M_1
Unit	kgm^2	kgm^2	kg	N/m	m	kg/m^3	Nm
Value	0.643	0.142	80.0	1960.0	0.18	900.0	50.0

tracking errors of knee joint trajectory, Fig. 6 is the torque of knee joint, Fig. 7 is the angular velocity of knee joint, and Fig. 8 is the opening value x of damp pin valve.

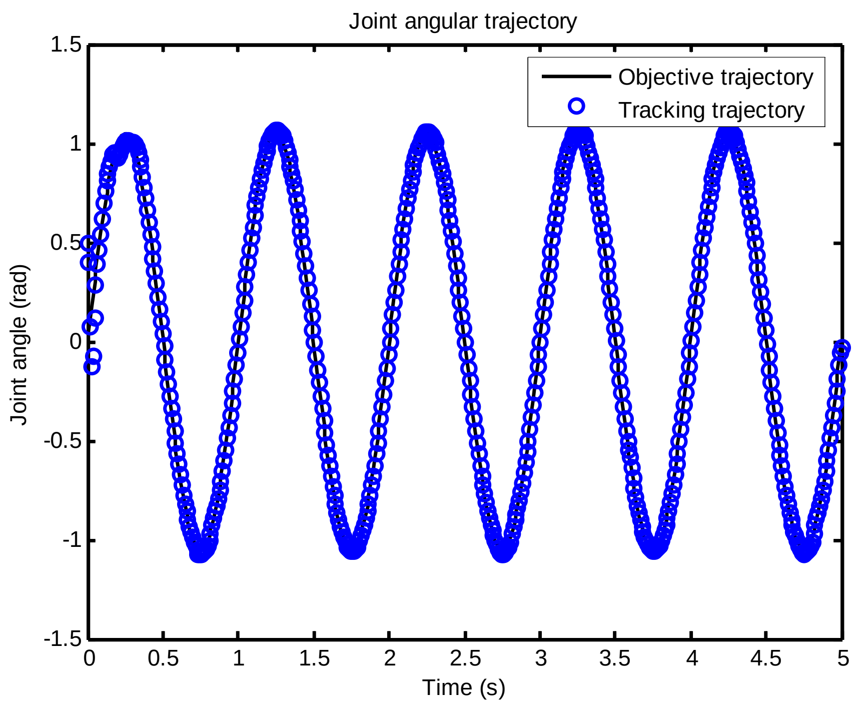


Fig. 4. Tracking trajectory of knee joint (Black real line denotes objective trajectory, and “o” line denotes tracking trajectory)

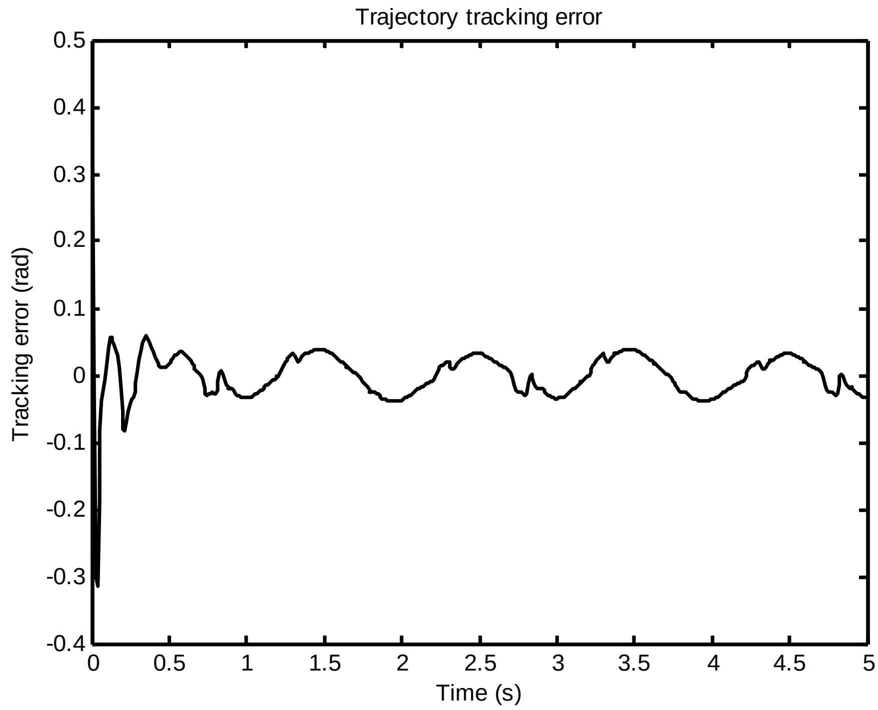


Fig. 5. Tracking errors of knee joint

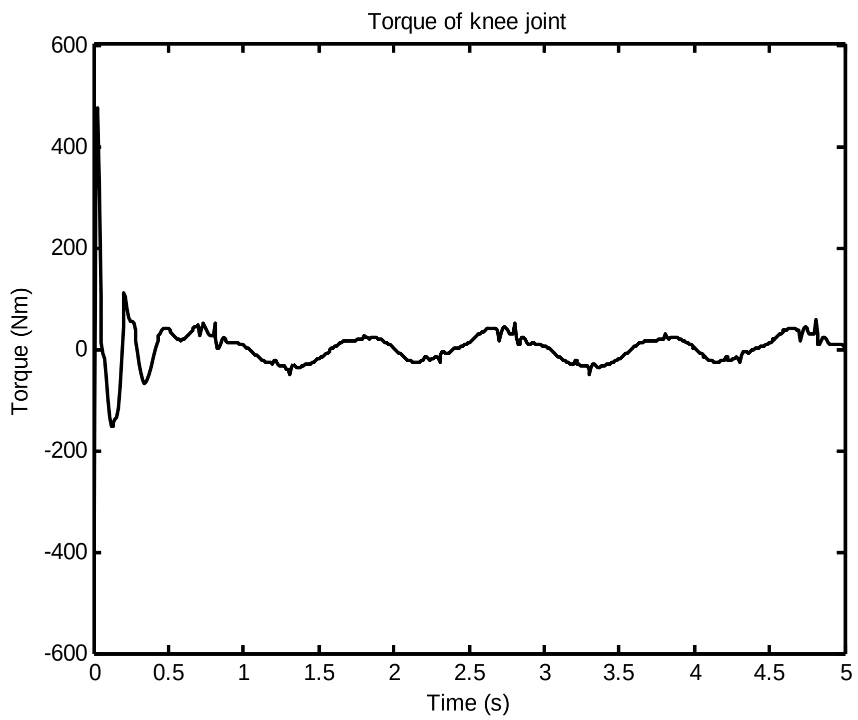
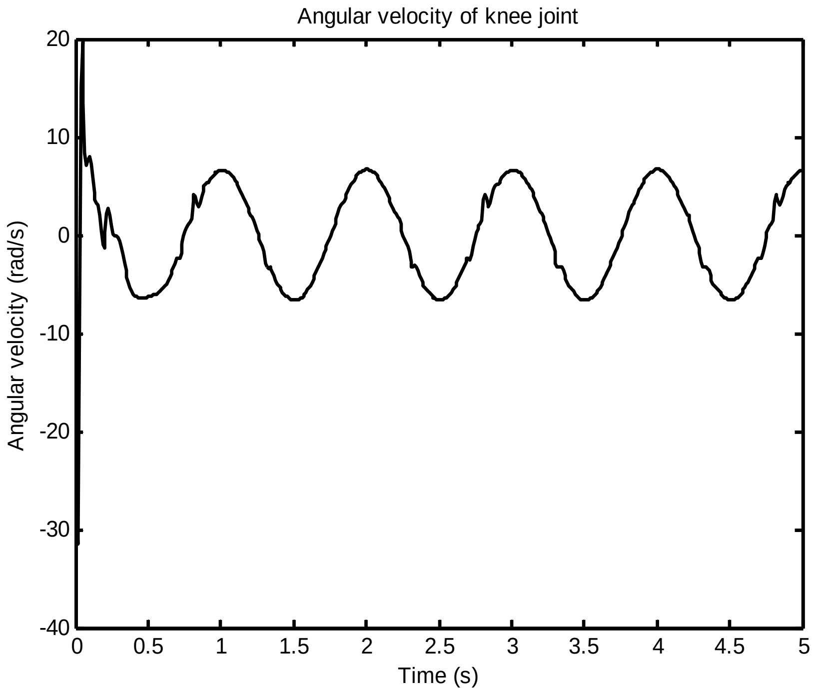
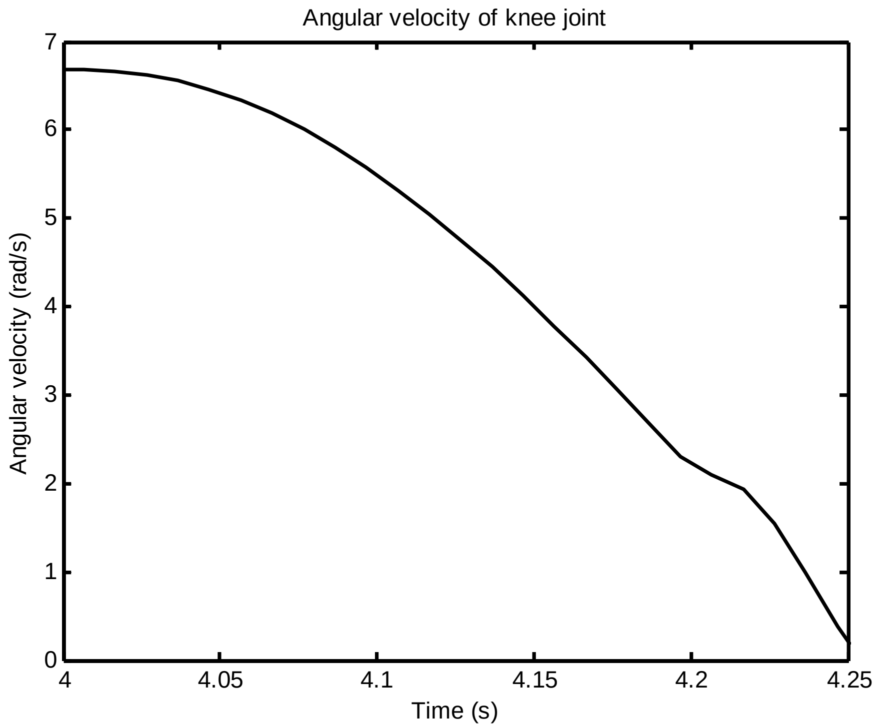


Fig. 6. Torque of knee joint

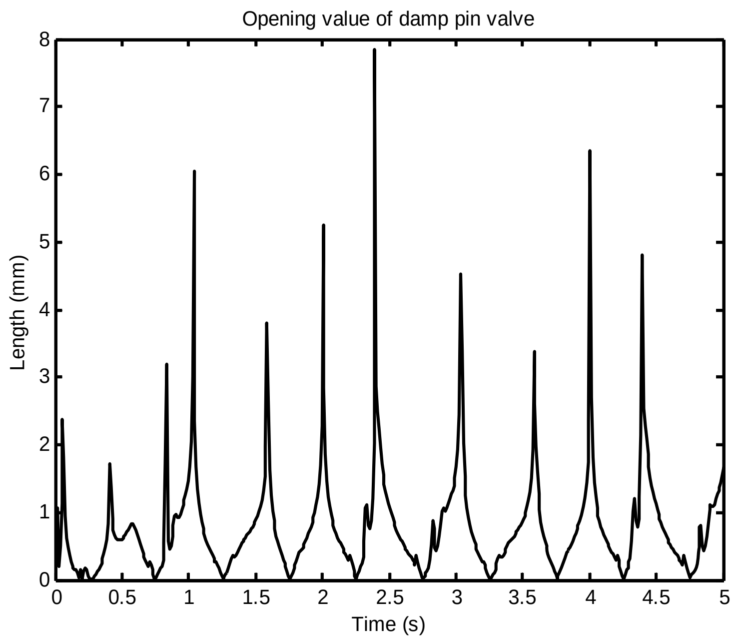


(a)

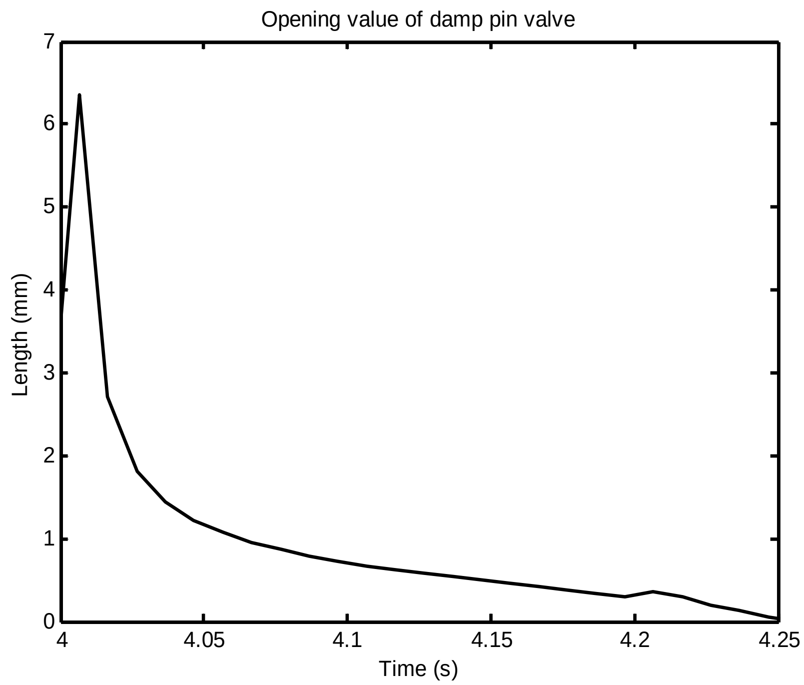


(b)

Fig. 7. Angular velocity of knee joint



(a)



(b)

Fig. 8. Opening value of damp pin valve

Fig. 6 denotes the actual resistance torque of IAL. In the IAL control system, the rotation velocity of knee joint is a key factor to gait symmetry. So, the angular velocity of knee joint is evaluated by Fig. 7(a). In fact knee joint is controlled by the opening value of damp pin valve, so opening value x is expressed by Fig. 8(a) based on dynamics model. In order to analyze system expediently, the value within 4s to 4.25s is expressed. Fig. 7(b) is angular velocity of knee joint, and Fig. 8(b) is opening value of damp pin valve respectively.

6 Conclusions

The simulation results lead to some conclusions as follows.

1. An arbitrary trajectory such as a desired walking pattern can be tracked in less than 0.5 seconds, which proves that the controller meets real time and precision demanded. It shows that gait (velocity) can be followed by PD-CMAC control through on-line detecting the knee pattern of healthy leg.
2. For IAL is only controlled by resistance torque on knee joint without active torque, the torque calculated from the simulation is just the damp torque on knee joint. It accords with the circular alternating law between damp torque trajectory and knee joint trajectory.
3. The opening position of damp pin valve has a remarkable relativity to angular velocity of knee joint in IAL. Furthermore, the angular velocity of knee joint will descend when the opening of damp pin valve is reduced. It accords with the actual motion during swing phase of human leg.

The dynamics model and simulation results show that PD-CMAC control,as a new control method, provides a significant theory model and method reference for IAL.

Acknowledgments

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