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RESEARCH ARTICLE

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Biped robot control strategy and open-closed-loop iterative learning control

Abstract Master-slaver dual-leg coordination control was proposed for the biped robot with heterogeneous legs (BRHL), in order to reduce gait planning and to get a good tracking performance. The key to coordination is gait trajectory tracking control. Bionic knee joint with closed-chain 4links makes robot walking more humanlike, but the model is complex and tracking of the bionic leg to the artificial leg is more difficult. P-type open-closed-loop iterative learning control (ILC) is not based on model parameters and has advantages in both open-loop and closed-loop ILC; so this paper proposes a complex robot gait trajectory tracking. The convergence is proved by using functional analysis and the stability condition is given. A tracking simulation based on the virtual prototype was done. The results show that this control strategy and algorithm are effective and robust, and the convergence speed is better than separate open-loop or closed-loop ILC.

Keywords BRHL, tracking, bionic knee joint, open-closed-loop iterative learning control, convergence, virtual prototype

1 Introduction

Exact gait trajectory tracking control, which is a nonlinear, strong coupling, and time-varying system, is an important aspect related to the walking of the biped robot. Feedback linearization with feedforward compensations, computed torque, variable structure sliding modes and self-adaptive control schemes has been used for this tracking control [1]. Learning control is the most effective control method and can accommodate modeling errors and varying environments. Based on Uchiyama's study on high-speed mechanical arm motion control, the concept of ILC was introduced first by Arimoto et al., motivated by robot's repetitive motion tasks [2,3]. Higher-order ILC was studied by Bien Z. et al. [4]. Arimoto tended to ignore factors in P-type ILC while improving tracking performance [5]. Chen Y. et al. added current feedback control in ILC [6]. The relation between ILC and conventional feedback control was discussed by Peter B. G. et al. [7]. Open-loop ILC and closed-loop ILC were studied independently in aforementioned ILC algorithms. Open-closed-loop ILC, including both open-loop and closed-loop ILC, is currently an active research direction.

The objective of this paper is to give control strategy an innovative BRHL. In this paper, trajectory tracking of complex robot is studied, and P-type open-closed-loop ILC scheme is proposed for tracking. Convergence is studied by using superposition method and functional analysis. Control simulation is done on virtual prototype and results demonstrate the effectiveness of this control scheme.

2 Trajectory tracking problem of biped robot

Control object is the innovative BRHL that is shown in Fig. 1. BRHL having 6 degree of freedom (DOF) is composed of an artificial leg of homogeneous biped robot, a bionic leg of intelligent prosthesis limb and a simple crotch. In Fig. 1, the parameters with superscript "*a*" and superscript "*b*" respectively denote variables of the artificial leg and the bionic leg. L is the link bar length, m is the mass, T is the control input torque, and θ is the generalized coordinate variable. Due to the use of closed-chain 4links knee joint, the bionic leg's instant center of rotation (ICR) is the point of intersection of ant-bar and post-bar prolongation. Trajectory of ICR is "*J*." With polycentric bionic knee joint, the bionic leg can acquire higher space between foot and ground, good dynamic characteristics like the human knee [8,9].

Using the Lagrangian method with constrains, the BRHL coordination dynamic model is established and given by Eq. (1), where ΔT is phase-different of dual leg. The first equation of Eq. (1) is the artificial leg's dynamics model $\sum_a$,

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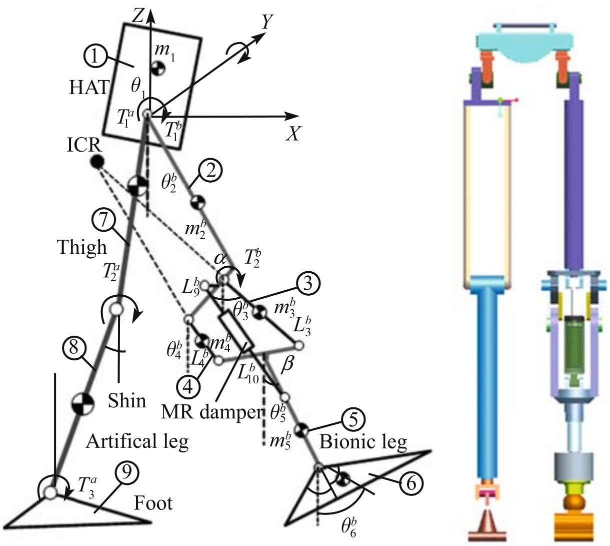

Fig. 1 The model of BRHL and virtual prototype

the second is the bionic leg's model Σ_b, the third is phase-different constrain and the fourth is 4links closed-chain constrain.

This paper proposes master-slaver dual-leg coordination control strategy for biped walking. Namely, real-time gait planning is done only for the artificial leg followed by the bionic leg tracking of this gait so as to reduce planning and computing time. The key to this control strategy, gait trajectory tracking problem, can be formulated as follows. In $t \in [0, T]$, to design a bounded control law guaranteeing $\theta^b(t+\Delta T) \rightarrow \theta^a(t) \rightarrow \theta^*(t)$, where $\theta^b(t)$ and $\theta^a(t)$ denote the gait trajectory of the artificial and the bionic leg respectively, $\theta^*(t)$ is the desired gait made by planning.

$$\begin{cases} \Sigma_a: M^a\left(\theta^a\right)\ddot{\theta}^a + C\left(\theta^a, \dot{\theta}^a\right) + G\left(\theta^a\right) + F^a\left(M_{\text{crotch}}\right) = T^a \\ \Sigma_b: M^b\left(\theta^b\right)\ddot{\theta}^b + C\left(\theta^b, \dot{\theta}^b\right) + G\left(\theta^b\right) + F^b\left(M_{\text{crotch}}\right) = T^b + F_{\theta^b}\lambda \\ \text{st}: \theta^b\left(t+\Delta t\right) = \theta^a\left(t\right) \\ \text{st}: -L_9^b e^{j\left(\theta_2^b - \alpha\right)} - L_3^b e^{j\theta_3^b} + L_{10}^b e^{j\left(\theta_5^b - \beta\right)} + L_4^b e^{j\theta_4^b} = 0 \end{cases} \quad (1)$$

Common trajectory tracking methods can get a good tracking performance and guarantee asymptotic stability, but they need exact model parameters. Bionic leg dynamics model with 4links closed-chain constrain contains pending multiplier $\dot{f}_{\theta^b}\lambda$, so it is more complex than artificial leg model and is difficult to solve. Therefore, it must be simplified. Because of the small mechanical size of 4links, links 3, 4 and 5 can be treated as a single link. According to varying ICR, the relation between driven torque and damper force is shown as Equation Section (Next) $T_2^b = F_d D_{\text{icr}}$, where F_d is MR damper force, and D_{ICR} is the distance between ICR and MR damper piston axis. Simplified model is easy to be controlled and computed, but simplifying model parameters errors enlarge tracking errors. So ILC is introduced in the tracking of biped robot with complex model and imprecise parameters in this paper.

3 P-type open-closed-loop iterative learning control

3.1 Control law

Open-loop ILC uses former tracking errors to perfect control input, and closed-loop ILC uses current tracking errors and can resist disturbing. All tracking errors are useful to form correct control input, so we propose open-closed-loop ILC to control BRHL. Let's consider Eq. (1) under the following control law

$$u_k = u_{k-1} + \Gamma e_k + \Gamma e_{k-1}, \text{ with } e = \theta^* - \theta \quad (2)$$

where Γ and Γ' are symmetric positive definite gain matrix of learning, k denotes the iteration number. Convergence condition of open-closed-loop ILC is different from other ILC [10]. Using functional analysis knowledge, convergence analysis procedure is given in the section that follows.

3.2 Convergence analysis

Under ILC, the state space of bionic leg system Σ_b at the iteration k can be expressed as

$$\begin{cases} \dot{x}_k(t) = f(t, x_k(t)) + B\left(t\right)u_k(t) \\ y_k(t) = g(t, x_k(t)) + D(t)u_k(t) \end{cases} \quad (3)$$

where $x = \left[\theta^b, \ \dot{\theta}^b\right]^{\mathrm{T}}$.

Suppose Eq. (3) satisfies the following reasonable assumptions.

Assumption 1 The function f and g are uniformly globally Lipschitz in x and u.

Assumption 2 For all k, the $\{\delta x_k(0)\}_{k \geqslant 0}$ satisfies $\lim_{k\rightarrow\infty} x_k\left(0\right) = x_d\left(0\right)$.

Assumption 3 There exists the desired u that guarantees the desired trajectory y.

Assumption 4 $(I + \Gamma(t)D(t))$ is not singular matrix.

Define

$$\begin{cases} \delta x_k(t) = x_d(t) - x_k(t) \\ \delta y_k(t) = y_d(t) - y_k(t) \\ \delta u_k(t) = u_d(t) - u_k(t) \\ f'(t, x(t), u(t)) = f(t, x_d(t), u_d(t)) \\ \qquad\qquad - f(t, x_d(t) - x(t), u_d(t) - u(t)) \\ g'(t, x(t)) = g(t, x_d(t)) - g(t, x_d(t) - x(t)) \end{cases} \quad (4)$$

From Eqs. (2), (3) and (4), we have

$$\begin{cases} \delta\dot{x}_k(t) = f'(t, \delta x_k(t), \delta u_k(t), \\ \delta u_k(t) = -\Gamma(t)(D(t)\delta u_k + g'(t, \delta x_k(t))) \\ \qquad\qquad - \Gamma'(t)(D(t)\delta u_{k-1} + g'(t, \delta x_{k-1}(t))) + \delta u_{k-1}(t) \end{cases} \quad (5)$$

Under Assumption 4, we have

$$\begin{aligned}\delta u_k(t) = &-(I+\Gamma(t)D(t))^{-1}\Gamma(t)g'(t,\delta x_k(t)) \\ &-(I+\Gamma(t)D(t))^{-1}\Gamma'(t)g'(t,\delta x_{k-1}(t)) \\ &+(I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))\delta u_{k-1}(t) \qquad (6)\end{aligned}$$

Define operator

$$\begin{aligned}&G_{k-1}:\ C_r[0,T]\to C_r[0,T],\ \text{as} \\ &G_{k-1}(u)(t) = (I+\Gamma(t)D(t))^{-1}\Gamma(t)g'(t,x(t)) \qquad (7)\end{aligned}$$

Then Eq. (6) can be written as

$$\begin{aligned}&\delta u_k(t)+G_{k-1}(\delta u_k)(t)+G_{k-1}(\delta u_{k-1})(t)= \\ &(I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))\delta u_{k-1}(t) \qquad (8)\end{aligned}$$

According to Bellman-Gronwall lemma and Ref. [11], we can define operator

$$\begin{aligned}&\bar{G}_{k-1}:\ C_r[0,T]\to C_r[0,T],\ \text{as} \\ &\bar{G}_{k-1}(v)(t) = G_{k-1}(u)(t),\ \forall v(t)\in c_r[0,T] \qquad (9)\end{aligned}$$

And there must exist exclusive $u(t)\in C_r[0,T]\lim\limits_{x\to\infty}$, that satisfies $u(t)+\mathrm{G}_{k-1}(u)(t)=v(t)$.

Define

$$\begin{aligned}&P(\delta u_{k-1})(t) = (I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))\delta u_{k-1}(t), \\ &Q_{k-1}(\delta u_{k-1})(t) = -\bar{G}_{k-1}(P\delta u_{k-1})(t) \qquad (10)\end{aligned}$$

where $P\delta u_{k-1}$ is the shortening of $P(\delta u_{k-1})(t)$.

Because of $P(\delta u_{k-1})(t)$ and $\delta u_k(t)$ both satisfy Eq. (8), we get

$$\begin{aligned}&\delta u_k(t)+G_{k-1}(\delta u_k)(t)+G_{k-1}(\delta u_{k-1})(t)= \\ &(I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))\delta u_{k-1}(t) \\ &=P(\delta u_{k-1})(t)\end{aligned}$$

According Ref. [11], we have

$$Q_{k-1}(\delta u_{k-1})(t) = -\bar{G}_{k-1}(P\delta u_{k-1})(t) = -G_{k-1}(\delta u_k)(t) \qquad (11)$$

From Eqs. (10) and (11), we have the transform of Eq. (8)

$$\delta u_k(t) = P(\delta u_{k-1})(t)+Q_{k-1}(\delta u_{k-1})(t)+G_{k-1}(\delta u_{k-1})(t) \qquad (12)$$

where operator G_{k-1} and Q_{k-1} are bounded and linear. Define bounded operator $Q'_{k-1}=Q_{k-1}+G_{k-1}$, where Q_{k-1} and G_{k-1} denote the operator existing in convergence proof of open-loop ILC and closed-loop ILC, respectively. Because P and Q'_{k-1} are bounded and linear, we have the transform of Eq. (12)

$$\delta u_k(t) = \left(P+Q'_{k-1}\right)(\delta u_{k-1})(t) \qquad (13)$$

Through recursive procedure, we obtain

$$\delta u_k(t) = \left(P+Q'_{k-1}\right)\left(P+Q'_{k-2}\right)\ \dots\ \left(P+Q'_0\right)(\delta u_0)(t) \qquad (14)$$

According to Eq. (14) and Ref. [11], we conclude that under condition $\rho(P)=\rho[(I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))]<1$, with $\forall t\in[0,T]$, then $\delta u_k(t)\to 0$ is guaranteed, and the control algorithm is consistent stability. The magnitude of $\Gamma(t)$ and $\Gamma'(t)$ can affect the convergence speed.

The sufficient condition of convergence of open-closed-loop ILC is $\rho[(I+\Gamma(t)D(t))^{-1}(I-\Gamma'(t)D(t))]<1$.

Based on the aforementioned proof, using reduction to absurdity method, the necessary condition is $\rho[(I+\Gamma(0)D(0))^{-1}(I-\Gamma'(0)D(0))]<1$.

4 Simulation results

In order to illustrate the validity of P-type open-closed-loop ILC, control simulation has been done on virtual prototypes of BRHL established by ADAMS, shown in Fig. 1. The bionic leg's hip joint gait trajectory is supposed to be the same as that of the artificial leg. Desired knee joint gait data is obtained from APAS, human motion measure software of Ariel Dynamics (US). Simulation period is 0.8 s, and sampling interval is 0.02 s, and control period is 0.005 s. Set $\Gamma=1$ and $\Gamma'=25$. The trajectory tracking of the bionic knee to the artificial knee and tracking root mean square (RMS) errors are illustrated in Figs. 2 and 3.

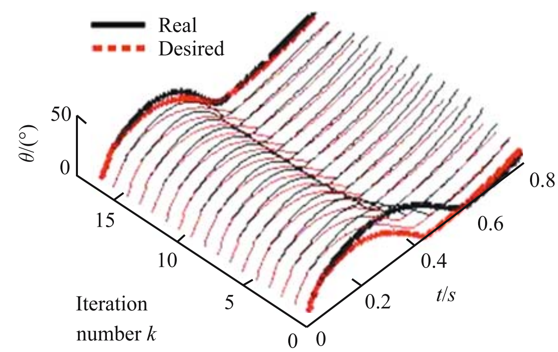

Fig. 2 Tracking curve of relative knee angle

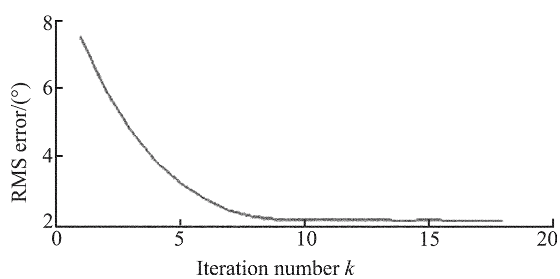

Fig. 3 RMS error curve

Fig. 4 illustrates RMS error of tracking, when white noise disturb is added to Eq. (3).

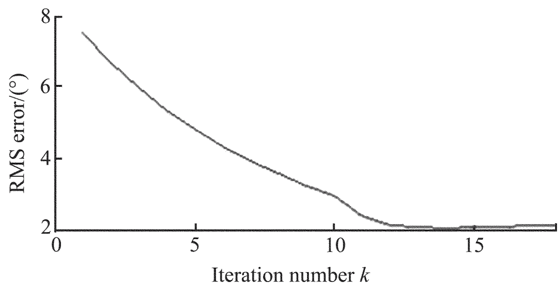

Fig. 4 RMS error curve of tracking with disturb

The errors are affected by initial error $\{\delta x_k(0)\}_{k\geqslant 0}$ and iteration number k. In biped robot repetitive walking control, the initial error is difficult to be reduced to zero. On satisfying the walking stability condition, the set will stop the judge of iteration as $E_{\text{RMS}} < 2$.

Under the same conditions, the open-loop ILC and closed-loop ILC for tracking are simulated on virtual prototypes and tracking results are shown in Table 1, in order to be compared with P-type open-closed-loop ILC.

Table 1 Convergence speed

Control scheme	Open-loop ILC	Closed-loop ILC	Open-closed-loop ILC
k	15	17	9

5 Conclusions

Master-slaver dual-leg coordination control strategy proposed by this paper can reduce gait planning and computing time. Simplified dynamics model of BRHL according to varying ICR is beneficial to control, but gives rise to parameters errors. P-type open-closed-loop ILC proposed by this paper does not need the precise model. The convergence can be proved by functional analysis, and stability sufficient condition is easy to be guaranteed by setting the right gain matrix of learning. Simulation on virtual prototypes of BRHL shows the tracking and anti-disturb ability of the control strategy and algorithms. The results show that open-closed-loop ILC is better than single open-loop or closed-loop ILC, and can be used for complex biped robot walking to facilitate an effective walking biped robot. Convergence speed is affected by gain of learning. Future research needs to focus on how to compute gain matrix of learning in order to get fast convergence speed.

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