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• **LETTER** •

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Composite following control for wheeled inverted pendulum vehicles based on human-robot interaction

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Dear editor,

Over the past decade, wheeled mobile robots have been widely used in many fields, and for the human-following, they are required to respect the social zones when they follow humans for the purpose of company or carrying loads [1–4]. To this end, an impedance control is proposed for a human-following robot Pioneer 3AT, where the parameters of the impedance function are obtained from an identification experiment in a human-human interaction [5]. However, if the robot in the human-robot formation is a wheeled inverted pendulum (WIP) vehicle that has the advantages of compact construction, high maneuverability and low energy consumption [6], the related control is encountered with such difficulties: (1) the forward movement of the WIP vehicle is decoupled with the steering movement, thus the distance between the vehicle and human cannot be regulated by a simple impedance control; (2) the WIP vehicle is a typical underactuated system, and it is important to control the tilt angle of vehicle body in a given domain during the motion process. These problems limit the application of WIP vehicle, but motivate this study in the meantime.

To fix these problems, a composite control method for the WIP vehicle in a human-robot formation is proposed based on human-robot interaction, which consists of a direct adaptive fuzzy controller (DAFC), a supervisory controller and an impedance controller. With DAFC, the direction of forward motion can be coincide with the line from the vehicle to the human. Then the distance between the vehicle and human can be controlled with the impedance controller to improve the social acceptance of the vehicle, and by the supervisory controller, the tilt angle of vehicle body can be controlled in a small domain given by the designer. Finally, an experimental study is performed to demonstrate the effectiveness of the proposed method.

Dynamic model. To facilitate the development of the control method, the dynamic model derived by Lagrangian approach [7] can be partitioned into three subsystems, as follows.

(1) Steering subsystem

$$\ddot{\varphi} = f_1 + g_1\tau_\omega, \tag{1}$$

where $f_1 = 0$, $g_1 = d/(2J_1 r)$, $J_1 = I_1 + I_3/2 + I_5/2 + (m_w + I_2/r^2)d^2/4$, $\tau_\omega = \tau_r - \tau_l$.

(2) Tilt angle subsystem

$$\ddot{\theta} = f_2 + g_2\ddot{x}_v, \tag{2}$$

where $f_2 = (2m_v m_b gL\sin\theta - \frac{m_b^3 gL^3\sin\theta\cos^2\theta}{2J_2})/F$, $F = 4m_v J_2 - m_b^2 L^2\cos^2\theta$, $g_2 = -m_b L\cos\theta/(2J_2)$, $J_2 = I_4/2 + I_6/2 + m_b L^2/2$, $m_v = I_2/r^2 + m_w + m_c/2 + m_b/2$.

(3) Forward subsystem

$$\ddot{x}_v = f_3 + g_3\tau_v, \tag{3}$$

where $f_3 = (2J_2 m_b L\dot{\theta}^2\sin\theta - m_b^2 gL^2\sin\theta\cos\theta)/F$, $g_3 = 2J_2/(Fr)$, $x_v = \dot{x}\cos\varphi + \dot{y}\sin\varphi$, $\tau_v = \tau_r + \tau_l$.

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Composite control method. The distance between the WIP vehicle and the human in a human-robot formation should be regulated properly to respect the social zone, as shown in Figure 1(a), which involves both the steering subsystem control and forward subsystem control.

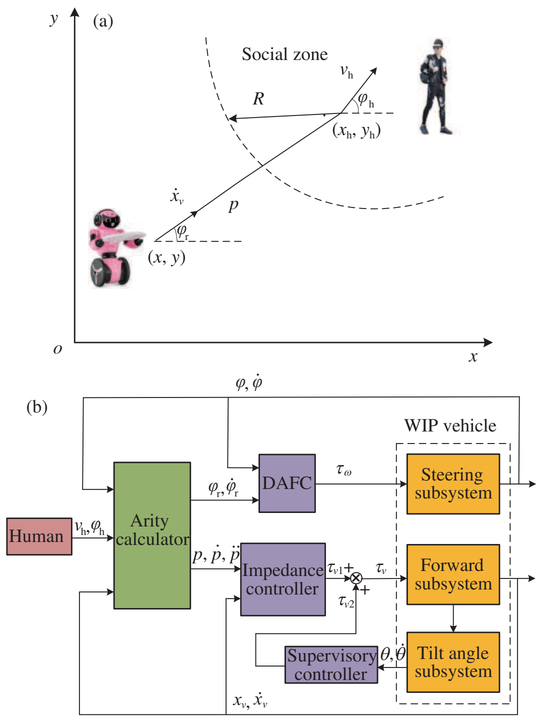

Figure 1 (Color online) (a) Human-robot formation; (b) scheme of the control system.

In particular, the tilt angle of vehicle body should be controlled in a small domain around zero to ensure the stability of the vehicle, which needs the effectively control of the tilt angle subsystem. However, the tilt angle subsystem can only be controlled through a coupling effect between the forward subsystem and the tilt angle subsystem because of the underactuated characteristic. To fix this problem, two virtual inputs τ_{v1} and τ_{v2} are introduced [7] to control the two subsystems, respectively, with the relation of $\tau_v = \tau_{v1} + \tau_{v2}$. Therefore, a composite control method for the WIP vehicle is developed, as shown in Figure 1(b), which will be described in detail in the following.

(i) Steering subsystem control. A DAFC is applied to make the steering angle φ track the reference one φ_r that can be calculated through the coordinates of the vehicle and the human. For example, $\varphi_r = \arctan \frac{y_h - y}{x_h - x}$, when $y_h - y \geqslant 0$ and $x_h - x > 0$, where x_h and y_h satisfy $\dot{x}_h = v_h \cos \varphi_h$, $\dot{y}_h = v_h \sin \varphi_h$.

(ii) Forward subsystem control. The interaction between the human leader and the vehicle follower can be described by a fictitious potential field that centered at the human with impedance characteristic [5], and the repulsion force from the human to the vehicle in the social zone can be expressed as

$$f_r(t) = \begin{cases} \chi \dfrac{\mathrm{e}^{-\frac{p^n(t)}{R}} - \mathrm{e}^{-R^{n-1}}}{1 - \mathrm{e}^{-R^{n-1}}}, & p(t) < R, \\ 0, & p(t) \geqslant R, \end{cases} \tag{4}$$

where $p(t) = \sqrt{(x_h - x)^2 + (y_h - y)^2}$ is the distance between the human and the vehicle, R is the radius of the social zone, χ is the maximum value of the force, and $n \in N$ is the order of the function.

Based on the above, the relationship between the distance error $\widetilde{x}_v(t) = R - p(t)$ and the interaction force $f_r(t)$ can be established through an impedance control [8], that is

$$f_r(t) = -(mz^2 + cz + k)\widetilde{x}_v(t), \tag{5}$$

where m, c and k are the inertial, damping, and the elastic parameter, respectively, and $z = \mathrm{d}/\mathrm{d}t$ is the time derivative operator.

Then, an experiment of impedance identification for a human-human interaction is conducted to lay the foundation for the human-robot interaction [5], and the related parameters are obtained as $n = 2$, $\chi = 100$, $R = 1.55$, $m = 0.35$, $c = 0.19$, and $k = 0.01$.

Next, to facilitate the design of control law τ_{v1}, Eq. (5) is rewritten as

$$f_r(t) = -m(\ddot{x}_v - \ddot{x}_{vr}) - c(\dot{x}_v - \dot{x}_{vr}) - k(R - p), \tag{6}$$

where $\dot{x}_{vr} = \dot{x}_v + \dot{p}$ and $\ddot{x}_{vr} = \ddot{x}_v + \ddot{p}$ are the velocity and acceleration of the human along the direction of the line between the human and the vehicle.

According to (3) and (6), the impedance control law based on human-robot interaction can be obtained as

$$\tau_{v1} = \frac{1}{g_3}\bigg(\ddot{x}_{vr} - f_3 - \frac{1}{m}(f_r(t) + c(\dot{x}_v - \dot{x}_{vr}) + k(R - p))\bigg). \tag{7}$$

Note that the control effect of (7) can reduce p when $p \geqslant R$, thus the WIP vehicle cannot always stay outside of the social zone.

(iii) Tilt angle subsystem control. A supervisory controller is constructed to control the tilt angle as follows:

$$\tau_{v2} = u_f + \rho u_s, \tag{8}$$

where u_f is a commonly used proportional derivative (PD) controller for the subsystem, ρ satisfies that $\rho = 0$ when $|\theta| \leqslant \delta$ and $\rho = 1$ when $|\theta| > \delta$,

δ is the bound of the tilt angle given by the designer [9], and u_s will be developed in the following.

Substituting (8) into (2), it obtains

$$\ddot{\theta} = f_2 + g_2(u_f + \rho u_s). \tag{9}$$

Then define the following expression:

$$u^* = \frac{1}{g_2}[-f_2 - \boldsymbol{k}^{\mathrm{T}}\boldsymbol{\theta}], \tag{10}$$

where $\boldsymbol{\theta} = [\theta, \dot{\theta}]^{\mathrm{T}}$, $\boldsymbol{k} = [k_2, k_1]^{\mathrm{T}}$, and the roots of $s^2 + k_1 s + k_2 = 0$ are on the left half plane.

Combining (9) and (10), it yields

$$\ddot{\theta} = -\boldsymbol{k}^{\mathrm{T}}\boldsymbol{\theta} + g_2[u_f - u^* + \rho u_s]. \tag{11}$$

Rearranging (11) as a vector form, it obtains

$$\dot{\boldsymbol{\theta}} = \boldsymbol{A}\boldsymbol{\theta} + \boldsymbol{b}[u_f - u^* + \rho u_s], \tag{12}$$

where

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 \\ -k_2 & -k_1 \end{bmatrix}, \quad \boldsymbol{b} = \begin{bmatrix} 0 \\ g_2 \end{bmatrix}.$$

On that basis, u_s can be developed with the form of

$$u_s = -\mathrm{sign}(\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{b})\left[\frac{1}{g_L}(f^U + |\boldsymbol{k}^{\mathrm{T}}\boldsymbol{\theta}|) + |u_f|\right], \tag{13}$$

where f^U and g_L are the upper bound of $|f_2|$ and the lower bound of $|g_2|$, respectively, which can be obtained by the skill of magnifying and shrinking; $\boldsymbol{P}$ and $\boldsymbol{Q}$ are both positive definite symmetric matrices that satisfy $\boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} = -\boldsymbol{Q}$.

Theorem 1. Given the initial value $|\theta(0)| \leqslant \delta$, the control law (8) can ensure $|\theta(t)| \leqslant \delta$ for $t \geqslant 0$.

Proof. Define a Lyapunov candidate function as

$$V = \frac{1}{2}\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{\theta}. \tag{14}$$

Taking the time derivative of (14), it yields

$$\dot{V} = \frac{1}{2}\dot{\boldsymbol{\theta}}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{\theta} + \frac{1}{2}\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\dot{\boldsymbol{\theta}}. \tag{15}$$

Taking (12) into (15) and rearranging that, it yields

$$\begin{aligned}\dot{V} &= -\frac{1}{2}\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{\theta} + \boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{b}[u_f - u^* + u_s] \\ &\leqslant |\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{b}|(|u_f| + |u^*|) + \boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{b}u_s. \end{aligned} \tag{16}$$

It can be concluded that $\dot{V} \leqslant 0$ after plugging (13) into (16), namely, the control law (8) can ensure $|\theta(t)| \leqslant \delta$ for $t \geqslant 0$.

Experimental study. An experiment for the proposed composite control method is conducted to validate its feasibility, where the experimental apparatus as shown in Figure S1 and the movement of the human is simulated by a reference trajectory $v_h = 0.1$ m/s, $\varphi_h = \pi/4$ rad. The results (see Figure S2 for details) show that the WIP vehicle can keep a proper distance from the human with the application of the human interaction dynamics, and the tilt angle of the vehicle body can be controlled in a small domain $|\theta| \leqslant 0.1$ rad given by the designer during the whole process.

Conclusion. A composite control method for the WIP vehicle in a human-robot formation is presented based on human-robot interaction, and the effectiveness of the proposed method is verified by the related experimental results.

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Supporting information Figures S1 and S2. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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