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Robust oscillation control of wheeled mobile robots

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Abstract: In the case when wheeled mobile robots run fast on rough surface, due to the body acceleration and oscillation, the sensors mounted on the robot body may be destroyed. In this paper, we propose a scheme to reduce the body acceleration at any specified location on the mobile robot body. To achieve this, a combined ideal robot model is designed. In the combined ideal robot model, the location where the acceleration performance becomes best can be moved easily by setting only two design parameters. Next, a robust model tracking controller is developed so that the behavior of an actual mobile robot tracks that of the combined ideal robot model. It is ascertained by numerical simulations that the body acceleration at any specified location can be improved easily and good robustness for uncertainties of robot mass, pitch and roll moment of inertia of robot body, and the position of the center of gravity is confirmed.

Keywords: Oscillation Control, Robust Tracking Control, Ideal Model, Wheeled Mobile Robot

I. INTRODUCTION

In extreme environment, for example, stricken area and planet surface, there are many dangerous tasks for human workers. Recently, in the environment, mobile robots working instead of human have been developed. Mobile robots developed until now are classified roughly into three large categories based on its mechanism, such as wheeled mobile robots[1]-[4], legged robots[5],[6], and articulated robots[7],[8]. Wheeled mobile robots with the high-speed mobility have an advantage in the case when it is required to gather information as soon as possible. In the developed wheeled mobile robots until now, the main focuses were concentrated on mechanisms to over steps and control scheme for a trajectory tracking. In the case when wheeled mobile robots run on rough surface at high-speed, due to the body acceleration and oscillation, the sensors mounted on the robot body may be destroyed and measurement accuracy of the sensors becomes worse. If instruments to reduce oscillation are equipped for every sensor, this problem can be resolved. However, this method is not suitable for small mobile robots.

Using actuators set at wheels axis, we can control the body acceleration and oscillation. This method is more suitable for small mobile robots. Therefore, in this paper, we propose a scheme to reduce the body acceleration at any specified location for mobile robots with actuators set at wheels axis. To achieve this end, a combined ideal robot model is designed based on the state space description containing the body acceleration. In the combined ideal robot model, the location where the acceleration performance becomes best can be moved easily by setting only two design parameters. Next, a robust model tracking controller is developed so that the behavior of an actual wheeled mobile robot tracks that of the combined ideal robot model.

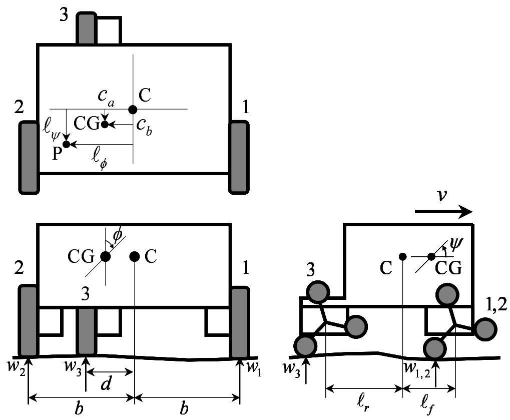


Fig. 1 Illustration of mobile robot

II. WHEELED MOBILE ROBOT

The wheeled mobile robot model is shown in Fig. 1. To simplify the explanation below, each large wheel is labeled as $1, 2, 3$. Each large wheel has three small wheels. In large wheel labeled 1 and 2, small wheels are driving wheels. The wheeled mobile robot has the mechanism that each large wheel can be rotated by the actuators set at the center of large wheels axis. In this paper, the control input to reduce the body acceleration is the voltage added to the actuators. The symbols O_n, I_n used below denote $n\times n$ zero matrix and $n\times n$ unit matrix.

1. Dynamic equation

It is assumed that the pitch angle $\psi(t)$ and the roll angle $\phi(t)$ are small, and then, dynamic equation of the wheeled mobile robot is given as follows. The explanation of parameters is shown in Table 1.

$$M_q\boldsymbol{q}(t)+k_dH^TH\dot{\boldsymbol{q}}(t)=-k_bH^T\boldsymbol{u}(t)+k_JH^T\boldsymbol{w}(t)+k_dH^T\dot{\boldsymbol{w}}(t)-(T_h^T)^{-1}M_c\boldsymbol{g} \quad (1)$$

Table 1. Notation of wheeled mobile robot

C, CG	center and center of gravity of mobile robot body
z_c	vertical displacement at C
ψ, ϕ	pitch and roll angle
x_1, x_2, x_3	vertical displacement at the center of large wheel
w_1, w_2, w_3	vertical displacement of road disturbance added to large wheels
v	longitudinal velocity of mobile robot
g	acceleration of gravity
m, i_ψ, i_ϕ	robot mass, pitch and roll moment of inertia of robot body
ℓ_f, ℓ_r, b, d	distance from C to large wheels
c_a, c_b	distance from C to CG
ℓ_ψ, ℓ_ϕ	distance from C to P
ℓ	distance from the center of large wheel to the center of small wheel
k_a	voltage and torque conversion constant
r, k_G	reciprocal of armature resistance and gear ratio
j_m, d_m	moment of inertia and viscous damping constant between a motor and wheel center axis

$$\left.\begin{aligned} \boldsymbol{q}(t) &= [z_c(t), \psi(t), \phi(t)]^T \\ \boldsymbol{u}(t) &= [u_1(t), u_2(t), u_3(t)]^T \\ \boldsymbol{w}(t) &= [w_1(t), w_2(t), w_3(t)]^T \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} M_q &= (T_h^T)^{-1} M_c (T_h)^{-1} + k_J H^T H \\ M_c &= \mathrm{diag}[m, i_\psi, i_\phi], \boldsymbol{g} = [g, 0, 0]^T \\ T_h &= I_3 - \boldsymbol{b}[0, c_a, c_b], k_b = \tfrac{4rk_a}{\sqrt{7}\ell k_G} \\ k_d &= \tfrac{16}{7\ell^2}(d_m + \tfrac{rk_a^2}{k_G^2}), k_J = \tfrac{16 j_m}{7\ell^2} \\ H &= \begin{bmatrix} 1 & \ell_f & -b \\ 1 & \ell_f & b \\ 1 & -\ell_r & d \end{bmatrix}, \boldsymbol{b} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \end{aligned}\right\} \quad (3)$$

Where $u_i(t), i = 1, 2, 3$ is the input voltage to motors at the center of large wheels axis. To simplify the design of a controller, the values of j_m, d_m, r, and k_a are the same in each large wheel.

2. Passive robot

We use the relation that the acceleration $\boldsymbol{y}(\ell_\psi, \ell_\phi, t) = [z_{\ell\psi,\ell\phi}(t), \psi(t), \phi(t)]^T$ at a location (ℓ_ψ, ℓ_ϕ) on the robot body can be described as $\boldsymbol{y}(\ell_\psi, \ell_\phi, t) = (I_3 + \boldsymbol{b}[0, \ell_\psi, \ell_\phi])\boldsymbol{q}(t)$. Where $z_{\ell\psi,\ell\phi}(t)$ denotes the vertical acceleration at the location (ℓ_ψ, ℓ_ϕ). In this paper, the proposed ideal robot model is designed based on the wheeled mobile robot using nominal values shown in Table 2. Using the relation $\boldsymbol{x}(t) = H\boldsymbol{q}(t) - \boldsymbol{w}(t)$, dynamic equation for the vertical displacement at the center of large wheels $\boldsymbol{x}(t) = [x_1(t), x_2(t), x_3(t)]^T$ is given by

$$\left.\begin{aligned} & M_p \boldsymbol{x}(t) + k_d \dot{\boldsymbol{x}}(t) = -k_b \boldsymbol{u}(t) + (k_J I_3 - M_p)\boldsymbol{w}(t) - (T_h^T)^{-1} M_c \boldsymbol{g} \\ & M_p = (H^T)^{-1} M_q H^{-1} \end{aligned}\right\}. \quad (4)$$

Table 2. Nominal values of parameters

m	84.2	kg	i_ψ	1.72	kgm^2
i_ϕ	1.39	kgm^2	ℓ	0.15	m
c_a	0.079	m	c_b	0.011	m
ℓ_f	0.125	m	ℓ_r	0.445	m
b	0.35	m	d	0.011	m
k_a	0.126	N/V	k_G	1/160	
j_m	0.21	kgm^2	d_m	1.73×10^{-4}	Nms/rad
r	0.226	$1/\Omega$			

To add a suspension characteristic to the wheeled mobile robot (4), the following input voltage is used.

$$\boldsymbol{u}(t) = \boldsymbol{u}_a(t) + \frac{k_p}{k_b}\boldsymbol{x}(t) + \frac{k_J}{k_b}\boldsymbol{w}(t) + \boldsymbol{u}_g. \quad (5)$$

Where $\boldsymbol{u}_a(t)$ is new input, $\boldsymbol{u}_g$ is the constant input voltage to hold the center of large wheels in a certain height, and k_p is feedback gain for the suspension characteristics.

To develop a controller achieving small acceleration of the robot body in the following section, the following state space description is introduced. The state is given by $\boldsymbol{\xi}(t) = [\boldsymbol{x}(t)^T, \dot{\boldsymbol{x}}(t)^T, (H\boldsymbol{q}(t))^T]^T$. It should be noted that the body acceleration $\boldsymbol{q}(t)$ is included in the new state $\boldsymbol{\xi}(t)$.

$$\left.\begin{aligned} \dot{\boldsymbol{\xi}}(t) &= (\quad + BF)\boldsymbol{\xi}(t) + B\boldsymbol{\mu}(t) + D_w \boldsymbol{w}(t) \\ \boldsymbol{\mu}(t) &= \dot{\boldsymbol{u}}_a(t) + \boldsymbol{u}_a(t) \end{aligned}\right\} \quad (6)$$

$$\left.\begin{aligned} & = \begin{bmatrix} O_3 & I_3 & O_3 \\ O_3 & O_3 & I_3 \\ O_3 & O_3 & O_3 \end{bmatrix}, B = \begin{bmatrix} O_3 \\ O_3 \\ -k_b M_p^{-1} \end{bmatrix}, D_w = \begin{bmatrix} O_3 \\ -I_3 \\ k_d M_p^{-1} \end{bmatrix} \\ & F = \tfrac{1}{k_b}[k_p I_3, (k_d + k_p) I_3, M_p + k_d I_3] \end{aligned}\right\} \quad (7)$$

Where $\boldsymbol{\mu}(t)$ is the new input to design a controller. The mobile robot (6) with $\boldsymbol{\mu}(t) = \boldsymbol{0}$ is called as the passive robot.

III. ROBUST TRACKING CONTROLLER

The control objective is to develop a robust controller so that the pitch and roll angle acceleration become small and the vertical acceleration at any specified location (ℓ_ψ, ℓ_ϕ) on the robot body can be reduced to small value easily. Hereafter, the location where the vertical acceleration becomes minimum will be called as the best location. To meet the objective, the following assumptions are made for an actual wheeled mobile robot considered here.

A1 The exact values of parameter except robot mass m, pitch and roll moment of inertia i_ψ, i_ϕ and the position of the center of gravity c_a, c_b are known and do not vary.

A2 Robot body accelerations $z_c(t), \psi(t), \phi(t)$ are measured.

A3 Vertical displacement at the center of large wheels $\boldsymbol{x}(t)$ and its velocity $\dot{\boldsymbol{x}}(t)$ are measured.

A4 Acceleration of road disturbance $\boldsymbol{w}(t)$ is measured and bounded.

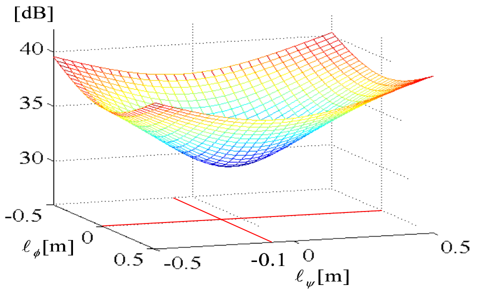
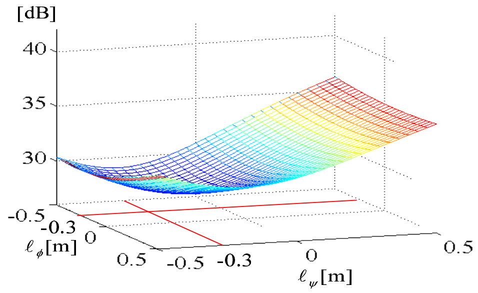
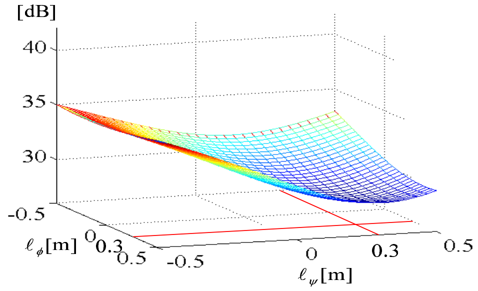


Fig. 2 Maximum gain surface of the passive robot



(a) $\ell_{\psi p} = -0.3, \ell_{\phi p} = -0.3$



(b) $\ell_{\psi p} = 0.3, \ell_{\phi p} = 0.3$

Fig. 3 Maximum gain surface of the combined ideal robot model

1. Combined ideal robot model

To develop a controller achieving the control objective, using the similar manner proposed in [9], a combined ideal robot model is proposed. The following ideal robot models are developed based on the wheeled mobile robot (6) using nominal values. In the explanation below, the symbol $\dagger_N$ denotes the matrix using nominal values.

$$\left.\begin{array}{l} \dot{\boldsymbol{\xi}}_m(t) = \quad \boldsymbol{\xi}_m(t) + B_N \boldsymbol{f}_m(t) + D_{wN}\boldsymbol{w}(t) \\ \boldsymbol{\xi}_m(t) = [\boldsymbol{x}_m(t)^T, \dot{\boldsymbol{x}}_m(t)^T, (H\boldsymbol{q}_m(t))^T]^T \\ \quad = \sum_{i=1}^{2} \gamma_{\phi i} \sum_{j=1}^{2} \gamma_{\psi j} \boldsymbol{\xi}_{m(2i+j-2)}(t) \end{array}\right\} \quad (8)$$

$$\left.\begin{array}{l} \boldsymbol{f}_m(t) = \sum_{i=1}^{2} \gamma_{\phi i} \sum_{j=1}^{2} \gamma_{\psi j} F_{m(2i+j-2)} \boldsymbol{\xi}_{m(2i+j-2)}(t) \\ \gamma_{\psi i} = \frac{(-1)^{i-1}\ell_{\psi p} + \ell_{\psi m}}{2\ell_{\psi m}}, \gamma_{\phi i} = \frac{(-1)^{i}\ell_{\phi p} + \ell_{\phi m}}{2\ell_{\phi m}}, i = 1, 2 \\ \boldsymbol{\xi}_{mi}(t) = [\boldsymbol{x}_{mi}(t)^T, \dot{\boldsymbol{x}}_{mi}(t)^T, (H\boldsymbol{q}_{mi}(t))^T]^T \\ \quad = \Omega_i \boldsymbol{\xi}_{di}(t), i = 1, 2, 3, 4 \\ F_{mi} = M_{pN} H T_i H^{-1} M_{pN}^{-1} (F_N - G_i)\Omega_i^{-1}, i = 1, 2, 3, 4 \\ \Omega_i = \mathrm{diag}[HT_iH^{-1}, HT_iH^{-1}, HT_iH^{-1}], i = 1, 2, 3, 4 \\ T_i = I_3 - \boldsymbol{b}[0, \ell_{\psi p} - \ell_{\psi m}, \ell_{\phi p} + (-1)^{i-1}\ell_{\phi m}], i = 1, 2 \\ T_i = I_3 - \boldsymbol{b}[0, \ell_{\psi p} + \ell_{\psi m}, \ell_{\phi p} + (-1)^{i-1}\ell_{\phi m}], i = 3, 4 \end{array}\right\} \quad (9)$$

The design parameters $\ell_{\psi p}, \ell_{\phi p}$ are introduced to specify the location where the vertical acceleration on the robot body must become minimum. The symbols $\boldsymbol{\xi}_{di}(t), i = 1, 2, 3, 4$ denotes the states for the ideal robot models given by

$$\left.\begin{array}{l} \dot{\boldsymbol{\xi}}_{di}(t) = (\quad + B_N(F_N - G_i))\boldsymbol{\xi}_{di}(t) + D_{wN}\boldsymbol{w}(t) \\ \boldsymbol{\xi}_{di}(t) = [\boldsymbol{x}_{di}(t)^T, \dot{\boldsymbol{x}}_{di}(t)^T, (H\boldsymbol{q}_{di}(t))^T]^T, i = 1, 2, 3, 4 \end{array}\right\} (10)$$

Where the feedback gains $G_i, i = 1, 2, 3, 4$ are designed for nominal robot

$$\left.\begin{array}{l} \dot{\boldsymbol{\xi}}_N(t) = (\quad + B_N F_N)\boldsymbol{\xi}_N(t) + B_N \boldsymbol{\mu}_N(t) + D_{wN}\boldsymbol{w}(t) \\ \boldsymbol{\xi}_N(t) = [\boldsymbol{x}_N(t)^T, \dot{\boldsymbol{x}}_N(t)^T, (H\boldsymbol{q}_N(t))^T]^T \end{array}\right\} (11)$$

so that the following quadratic criterion becomes minimum.

$$\left.\begin{array}{l} J = \int_0^\infty (\boldsymbol{q}_{Ni}(t)^T E_{qi} \boldsymbol{q}_{Ni}(t) + \boldsymbol{x}_N(t)^T E_{xi} \boldsymbol{x}_N(t) \\ \quad + \dot{\boldsymbol{x}}_N(t)^T E_{dxi} \dot{\boldsymbol{x}}_N(t) + \boldsymbol{\mu}_N(t)^T R_i \boldsymbol{\mu}_N(t)) dt \\ \boldsymbol{q}_{Ni}(t) = [z_{Ni}(t), \theta_N(t)]^T, i = 1, 2, 3, 4 \end{array}\right\} (12)$$

The symbols $E_{qi}, E_{xi}, E_{dxi}, R_i, i = 1, 2, 3, 4$ in (12) denote the weight matrixes for the ideal robot models $\boldsymbol{\xi}_{di}(t), i = 1, 2, 3, 4$. The signals $z_{Ni}(t), i = 1, 2, 3, 4$ denote the vertical acceleration at the specified location $(\ell_\psi = \ell_{\psi m}, \ell_\phi = (-1)^i \ell_{\phi m}), i = 1, 2$ and $(\ell_\psi = -\ell_{\psi m}, \ell_\phi = (-1)^i \ell_{\phi m}), i = 3, 4$. Using the positive definite solution of the Riccati equation

$$\left.\begin{array}{l} (\quad + B_N F_N)^T P_i + P_i(\quad + B_N F_N) - P_i B_N R_i^{-1} B_N^T P_i = -Q_i \\ Q_i = \mathrm{diag}[E_{xi}, E_{dxi}, Q_{qi}], i = 1, 2, 3, 4 \\ Q_{qi} = (H^T)^{-1}(I_3 + \boldsymbol{b}[0, \ell_{\psi m}, (-1)^i \ell_{\phi m}])^T \\ \quad \times E_{qi}(I_3 + \boldsymbol{b}[0, \ell_{\psi m}, (-1)^i \ell_{\phi m}]) H^{-1}, i = 1, 2 \\ Q_{qi} = (H^T)^{-1}(I_3 + \boldsymbol{b}[0, -\ell_{\psi m}, (-1)^i \ell_{\phi m}])^T \\ \quad \times E_{qi}(I_3 + \boldsymbol{b}[0, -\ell_{\psi m}, (-1)^i \ell_{\phi m}]) H^{-1}, i = 3, 4 \\ E_{qi} = (I_3 + \boldsymbol{b}[0, \ell_{\psi qi}, \ell_{\phi qi}])^T \mathrm{diag}[e_z, e_\psi, e_\phi] \\ \quad \times (I_3 + \boldsymbol{b}[0, \ell_{\psi qi}, \ell_{\phi qi}]), i = 1, 2, 3, 4 \end{array}\right\}, (13)$$

a controller to minimize the criterion (12) is given by

$$\boldsymbol{\mu}_N(t) = -R_i^{-1} B_N^T P_i \boldsymbol{x}_N(t) = -G_i \boldsymbol{x}_N(t), i = 1, 2, 3, 4. \quad (14)$$

The weight matrixes are set so that the vertical acceleration $z_{Ni}(t), i = 1, 2, 3, 4$ becomes minimum, respectively.

The transform matrix $\Omega_i, i = 1, 2, 3, 4$ is introduced to move the location where the vertical acceleration becomes minimum in $\boldsymbol{\xi}_{mi}(t), i = 1, 2, 3, 4$. The combined ideal robot model (8) is designed by combining the ideal robot models $\boldsymbol{\xi}_{mi}(t), i = 1, 2, 3, 4$ linearly. In the combined ideal robot model, the best location can be moved easily by setting the only two design parameters $\ell_{\psi p}$ and $\ell_{\phi p}$.

Figs. 2, 3 show the properties of the passive robot and the proposed combined ideal robot model. To show the gain characteristics relating to the vertical acceleration on the robot body, the maximum value of the norm of transfer function vector from the derivative of road disturbance $\dot{\boldsymbol{w}}(t)$ to the vertical acceleration $z_{\ell\psi,\ell\phi}(t)$ at a location (ℓ_ψ, ℓ_ϕ) is plotted with respect to 10Hz or less frequency of the derivative of road disturbance. Hereafter, the curved surface such as shown in Figs. 2, 3 are called as the maximum gain surface. Fig. 2 shows the maximum gain surface of the passive robot and Fig. 3 shows that of the combined ideal robot model. The two design parameters $\ell_{\psi p}, \ell_{\phi p}$ are set as $\ell_{\psi p} = -0.3, \ell_{\phi p} = -0.3$ in Fig. 3 (a) and $\ell_{\psi p} = 0.3, \ell_{\phi p} = 0.3$ in Fig. 3 (b). It can be seen from Fig. 3, in the combined ideal robot model, the best location can be moved easily by setting the only two design parameters $\ell_{\psi p}$ and $\ell_{\phi p}$.

As stated above, even if actual mobile robot parameters such as robot mass, pitch and roll moment of inertia of robot body, and the position of the center of gravity include uncertainties, the control objective can be achieved if the behavior of the actual wheeled mobile robot tracks that of the combined ideal robot model (8).

2. Trajectory tracking controller

In order to develop a robust controller achieving the control objective, the tracking error between the actual wheeled mobile robot (6) and the combined ideal robot model (8) is defined as $\widetilde{\boldsymbol{\xi}}(t) = \boldsymbol{\xi}(t) - \boldsymbol{\xi}_m(t)$. Then, the tracking error equation is given by

$$\dot{\widetilde{\boldsymbol{\xi}}}(t) = {}_{\xi}\widetilde{\boldsymbol{\xi}}(t) + B_{\xi} M_p^{-1}(-k_b \boldsymbol{\mu}(t) - \boldsymbol{\omega}_1(t) + M_{pN}\boldsymbol{\omega}_2(t) + \Theta\boldsymbol{\omega}(t)), \quad (15)$$

$$\left.\begin{array}{l} {}_{\xi} = \begin{bmatrix} O_3 & I_3 & O_3 \\ O_3 & O_3 & I_3 \\ -I_3 & -3I_3 & -3I_3 \end{bmatrix}, B_{\xi} = \begin{bmatrix} O_3 \\ O_3 \\ I_3 \end{bmatrix} \\ \Theta = M_p M_{pN}^{-1} - I_3, \boldsymbol{\omega}(t) = M_{pN}\boldsymbol{\omega}_2(t) + k_d \boldsymbol{w}(t) \\ \boldsymbol{\omega}_1(t) = k_p \boldsymbol{x}(t) + (k_d + k_p)\dot{\boldsymbol{x}}(t) + k_d H \boldsymbol{q}(t) \\ \boldsymbol{\omega}_2(t) = k_b M_{pN}^{-1} \boldsymbol{f}_m(t) - H\boldsymbol{q}(t) + \widetilde{\boldsymbol{x}}(t) + 3\dot{\widetilde{\boldsymbol{x}}}(t) + 3H\widetilde{\boldsymbol{q}}(t) \end{array}\right\}. \quad (16)$$

Where Θ is unknown matrix and $\boldsymbol{\omega}(t), \boldsymbol{\omega}_i(t), i = 1, 2$ are known signal vectors. The developed robust controller is given by

$$\boldsymbol{\mu}(t) = \frac{1}{k_b}(-\boldsymbol{\omega}_1(t) + M_{pN}\boldsymbol{\omega}_2(t) + \alpha B_{\xi}^T P_{\xi}\widetilde{\boldsymbol{\xi}}(t)). \quad (17)$$

The positive definite matrix P_{ξ} is the solution of the following Lyapunov equation.

$${}_{\xi}^{T} P_{\xi} + P_{\xi}\ {}_{\xi} = -\beta I_9 \quad (18)$$

Where α and β are the positive design parameters.

In the controlled wheeled mobile robot using the controller (17), the following theorem holds.

Theorem 1 The controlled wheeled mobile robot using the controller (17) becomes stable, and by analyzing the time derivative of $V(t) = \widetilde{\boldsymbol{\xi}}(t)^T P_{\xi}\widetilde{\boldsymbol{\xi}}(t)$,the following inequality can be obtained.

$$\dot{V}(t) \leq -\beta\widetilde{\boldsymbol{\xi}}(t)^T\widetilde{\boldsymbol{\xi}}(t) + \frac{\overline{\rho}}{\alpha} \quad (19)$$

where $\overline{\rho}$ is a bounded constant independent of the design parameter α.

It can be concluded from the theorem 1 that the tracking performance can be improved easily by setting the design parameters α and β as large enough.

IV. CONCLUSION

We have proposed the new scheme to achieve good acceleration performance at any specified location on the wheeled mobile robot body. For lack of space, the simulation results for the actual wheeled mobile robot using the developed controller are not shown. However, the following properties have been ascertained by carrying out numerical simulations. Using the proposed scheme, by setting the only two design parameters $\ell_{\psi p}$ and $\ell_{\phi p}$, the location where the acceleration performance becomes best can be moved easily without redesigning a controller. Moreover, good acceleration performance can be achieved even if the actual wheeled mobile robot parameters include uncertainties, such as robot mass, pitch and roll moment of inertia of robot body, and the position of the center of gravity. This research is sponsored by the Robotics Industry Development Council.

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