Periodic Adaptive Compensation of State-dependent Disturbance in a Digital Servo Motor System

Hyo-Sung Ahn, YangQuan Chen, and Wonpil Yu

Abstract: This paper presents an adaptive controller for the compensation of state-dependent disturbance with unknown amplitude in a digital servo motor system. The state-dependent disturbance is caused by friction and eccentricity between the wheel axis and the motor driver of a mobile robot servo system. The proposed control scheme guarantees an asymptotical stability for both the velocity and position regulation. An experimental result shows the effectiveness of the adaptive disturbance compensator for wheeled-mobile robot in a low velocity diffusion tracking. A comparative experimental study with a simple PI controller is presented.

Keywords: Adaptive control, mobile robot, servo motor control, state-dependent disturbance.

1. INTRODUCTION

In the wheeled-mobile robot applications, the robot is often required to follow a predefined route with a desired velocity profile. In tracing a typical diffusion process described by partial differential equation [1], the robot is required to move with a relatively slow velocity while tracing the diffusion boundary accurately. The effects caused by friction and eccentricity inside the wheeled-mobile robot and other parasitic effects may lead to a steady-state tracking error and limit cycles in velocity regulation. Model-based control strategy is proved to be not effective in practice for such kind of problem. One reason is that the accurate model for the source of the disturbance is not available, and the other reason is that, for the servo motor on the wheeled-mobile robot, especially for low cost, small-scale mobile robot, the exact servo model is also hard to obtain. With a lack of precise knowledge on the external disturbance and the servo model, the disturbance compensation based on adaptive control strategy is more practical.

Lots of research effort has been devoted to the adaptive control strategy for compensating the external disturbance [2-5]. It is shown that the external disturbance is a state-dependent or position-dependent periodic disturbance for rotary systems [4] [5,6]. In [7], the friction force is a state-dependent parasitic effect. In [8-11], the engine crankshaft speed pulsation, tire/road contact friction, and cogging force are modeled as state-dependent disturbances.

In our experiment, the position-dependent disturbance is conspicuous as shown in Fig. 1 for an open-loop velocity servo control (see Fig. 2 for the wheeled-mobile robots used in our test). Here, the desired velocity set-point is 2π rad/s. The actual velocity follows a sinusoid-like trajectory. It clearly shows that the external disturbance can be modeled as a function of position with a period of 2π. This corresponds to one rotation of the wheel. As observed in our experiments, the effect caused by external state-dependent disturbance is more severe in low velocity scenario [7].

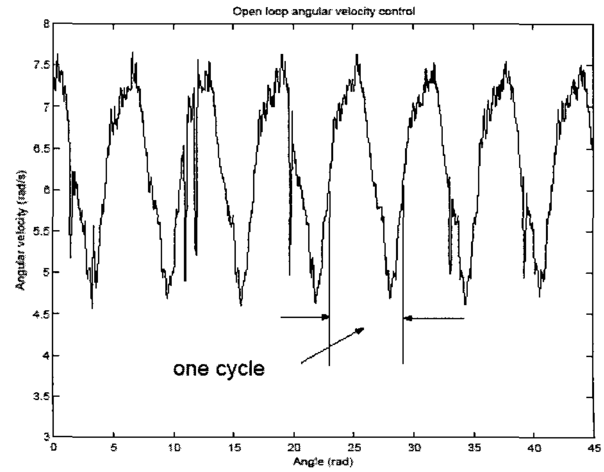


Fig. 1. The position-dependent disturbance in angular velocity regulation.

Manuscript received April 29, 2006; revised January 12, 2007; accepted March 8, 2007. Recommended by Editorial Board member Sooyong Lee under the direction of Editor Jae-Bok Song. The first author acknowledges the previous and current MAS-net team members for their efforts in building MASmotes and MAS-net platform.

Hyo-Sung Ahn and Wonpil Yu are with Intelligent Robot Research Division, Electronics and Telecommunications Research Institute (ETRI), 161 Gajeong-dong, Yuseong-gu, Daejeon 305-700, Korea (e-mails: {hyosung, ywp}@etri.re.kr).

YangQuan Chen is with the Dept. of Electrical and Computer Engineering, Utah State University, 4160 Old Main Hill, UT 84322-4160, USA (e-mail: yqchen@ece.usu.edu).

Recently some research works have been devoted to design an adaptive controller for compensating the state-dependent disturbance. In [12], an adaptive disturbance cancellation problem is solved by using a velocity-dependent internal model of the eccentricity. This method is computationally not effective in real applications, especially for a computation-constrained low cost, small-scale wheeled-mobile robot. The eccentricity may not dominate in external disturbance.

In this paper, we propose a simple state-dependent adaptive compensation technique which can be used to compensate the external disturbance for rotary mechanical system in wheeled-mobile robot. This new technique is designed based on the previous works in [5,10,14]. The basic idea of this adaptive scheme is to utilize the state-periodic information on the time axis. The remaining part of this paper is organized as follows. In Section 2, problem formulation and an adaptive controller are introduced. In Section 3, we will concentrate on an adaptive controller design for the rotary problem in wheeled-mobile robots. Section 4 is devoted to the small-scale wheeled-mobile robot for diffusion tracking and we will show how to obtain the parameters of robot model for a controller design. To show the effectiveness of our proposed adaptive compensator for external disturbance, an experimental evaluation is presented with a comparative study with a PI controller in Section 5. Finally, conclusions and some remarks on our further investigations are presented in Section 6.

2. STATE-DEPENDENT ADAPTIVE COMPENSATOR

In this section, the state-periodic adaptive compensator, which was suggested in [5,10,14] is briefly reviewed. Without loss of generality, consider a simple servo control system modeled by:

$$\dot{x}(t) = v(t), \tag{1}$$

$$\dot{v}(t) = -a(x) + u, \tag{2}$$

where x is the position (θ); $a(x)$ is the unknown state-dependent disturbance; v is the velocity; and u is the control input. It is assumed that the rotation direction does not change (from forward to backward, or backward to forward) for the whole process. To derive an adaptive control law for the disturbance compensation, the following definitions are necessary.

Definition 1: The total passed trajectory s is given as $s = \int_0^t (|dx(\varsigma)|/d\varsigma)_{\varsigma=\tau} d\tau = \int_0^t |v(\tau)| d\tau$, where $x(t)$ is the position and $v(t)$ is the velocity.

Definition 2: The periodic trajectory s_p is defined as the length of the trajectory to finish one periodic movement. This periodic trajectory is 2π in the angular velocity control for the rotary system.

Definition 3: Since the disturbance appears as a function of the position and the desired trajectory to be followed is assumed to be repetitive in rotary system, the external disturbance is also periodic with respect to position. So, based on Definitions 1 and 2, the following relationships are true.

$$a(s) = a(s - s_p) \tag{3}$$

$$x(s) = x(s - s_p), \quad s_p = 2\pi \tag{4}$$

With the above definitions, the following property is observed.

Property 1: The current disturbance is equal to one-trajectory past disturbance. That is,

$$a(t) = a(s(t)) = a(s(t) - s_p) = a(t - P_t), \tag{5}$$

where P_t is the time to complete one repetitive trajectory s_p at time instant t.

In the stability analysis, the following notations are used: $e_a(s(t)) = a(s(t)) - \hat{a}(s(t))$, $e_v = v(t) - v_d(t)$, where $\hat{a}(s(t)) = \hat{a}(t)$ is an estimated external disturbance and $v_d(t)$ is a desired velocity profile. Here, let us change $e_a(s(t)) = a(s(t)) - \hat{a}(s(t))$ into time domain as:

$$e_a(s(t)) = a(s(t)) - \hat{a}(s(t)) = a(t) - \hat{a}(t) = e_a(t). \tag{6}$$

Similarly, we have $x(s(t)) = x(t)$; $x_d(s(t)) = x_d(t)$; $v(s(t)) = v(t)$; and $v_d(s(t)) = v_d(t)$. The adaptive disturbance compensator is expected to track the given desired position $x_d(t)$ and the corresponding desired velocity $v_d(t)$ with tracking errors as small as possible. In practice, it is reasonable to assume that $x_d(t)$, $v_d(t)$ and $\dot{v}_d(t)$ are all bounded. The feedback control law is designed as:

$$u = \hat{a}(t) + \dot{v}_d(t) - (\alpha + \lambda)e_v(t) - \alpha\lambda\, e_x(t), \tag{7}$$

where α and λ are positive gains; $\dot{v}_d(t)$ is the desired acceleration; and $e_x(t) = x(t) - x_d(t)$ is the position tracking error. The adaptation law is designed as follows:

$$\hat{a}(t) = \begin{cases} \hat{a}(t - P_t) - K(e_v(t) - \lambda e_x(t)) & \text{if } s \geq s_p \\ z - g(v(t)) & \text{if } s < s_p, \end{cases} \tag{8}$$

where $\hat{a}(t - P_t) = \hat{a}(s - s_p)$; K is a positive design parameter called the periodic adaptation gain; z will be defined in Sec. III; and $g(v(t))$ is a tuning function to be selected based on the guideline $1/4 < g'(v) = \partial g(v)/\partial v < \infty$. Now, based on the above discussions, the following stability analysis is carried out. Our compensation approach is to ensure l_2 stability when $s < s_p$ and to stabilize the system when $s \geq s_p$. Let us investigate the case of $s \geq s_p$ first. The following results are adopted from our previous work [5] without proof.

Lemma 1: Using the notation $\theta(t) := e_v(t) + \lambda\, e_x(t)$, when $s \geq s_p$, the control law (7) and the periodic adaptation law (8) guarantee the asymptotical stability of the equilibrium points $\theta(t)$ and $e_a(s(t))$ as $t \to \infty (s \to \infty)$.

The above lemma only guarantees the asymptotical stability property of $\theta(t)$ (i.e., it does not guarantee the asymptotical stability of $e_x(t)$ and $e_v(t)$). The asymptotical stability of $e_x(t)$, $e_v(t)$ and $e_a(t)$ was given in [5] like the below lemma.

Lemma 2: If the initial position (x_0) is at the desired initial position $(x_d(0))$, i.e., $e_x(0) = 0$, then the control law (7) and the periodic adaptation law (8) guarantee the asymptotically stability of the equilibrium points $e_x(t)$, $e_v(t)$, and $e_a(t)$ as $t \to \infty$ $(t \geq P_1)$.

Next, let us consider the case when $s < s_p$.

Lemma 3: If $e_x(0) = 0$, $|\dot{a}|$ is bounded, and $g'(v) > 1/4$, then the equilibrium points of $e_x(t)$, $e_v(t)$ and $e_a(t)$ are asymptotically stable as $t \to \infty$ $(s \to \infty)$.

The design guide of $g(v)$ is given in [5].

3. CONTROLLER DESIGN FOR ROTARY SYSTEM

In typical applications of the wheeled-mobile robots, the state-dependent disturbance compensation problem in the rotary system is formulated as follows:

$$\dot{\theta}(t) = w(t), \tag{9}$$

$$J\dot{w}(t) = -a(\theta(t)) + \tau(t), \tag{10}$$

where $\theta(t)$ is angle, $w(t)$ is angular rate, $a(\theta(t))$ is unknown angle-dependent disturbance, J is the moment of inertia of the rotating wheel, and τ is the control torque. Based on Lemma 2 and Lemma 3, the following theorem is derived:

Theorem 1: Let the control law be given as $\tau(t) = J\tau'(t)$ with

$$\tau'(t) = \hat{a}'(t) + \dot{w}_d(t) - (\alpha + \lambda)e_w(t) - \alpha\lambda\, e_\theta(t), \tag{11}$$

where $e_w(t) = w(t) - w_d(t)$ and $e_\theta(t) = \theta(t) - \theta_d(t)$, and the adaptation laws be given as

$$\hat{a}'(t) = \begin{cases} \hat{a}'(t - P_t) - K(e_w(t) - \lambda\, e_\theta(t)) & \text{if } s \geq 2\pi \\ z - g(w(t)) & \text{if } s < 2\pi, \end{cases} \tag{12}$$

where $g(w(t)) = \xi\, w(t) + e^{-\mu\, w(t)}$, $\xi > \mu + 1/4$ and $\dot{z} = (\xi - \mu e^{-\mu\, w(t)})(\tau - \hat{a}'(t))$. Then, with zero initial angle error, i.e., $e_\theta(0) = 0$, the equilibrium points $e_\theta(t)$, $e_w(t)$, and $e_a(t)(= a(t) - \hat{a}(t))$ of (9-10) are asymptotically stable as $t \to \infty (s \to \infty)$.

Proof: Substituting $-a(\theta(t))/J = -a'(\theta(t))$ and $\tau(t)/J = \tau'(t)$, and using Lemma 2 and Lemma 3, the proof can be completed. □

Remark 1: In the rotary system, the following equality is true:

$$\int_t^{t-P_t} |d\theta(\varsigma)/d\varsigma|_{\varsigma=\tau}\, d\tau = 2\pi. \tag{13}$$

So, P_t can be calculated by an interpolation at every time instant t. For more detailed explanation, see [11].

4. WHEELED-MOBILE ROBOT DESIGN AND PARAMETER ESTIMATION

4.1. Hardware and software design for WMR

The proposed adaptive controller for external disturbance compensation has been applied on the wheeled-mobile robots-MASmote [1,13]. The main objective of this project is to integrate the actuators into the sensor network to extend the network sensing capability for diffusion tracking. Fig. 2 shows MAS mote, the wheeled-mobile robot for actuator/sensor network. Fig. 2 shows the robot body side profile with encoder. For a large-scale actuator/sensor network application, low-cost and small size wheeled-mobile platform was developed. The pulse produced at every count on the encoder can trigger an interruption on the CPU. The angular velocity of the wheel is measured from the time interval between two successive pulses. In our experiment, we can display the measurements of the motor angular velocity on screen in real time.

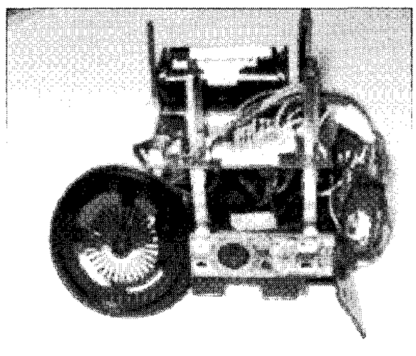


Fig. 2. Wheeled-mobile robot for actuator/sensor network: MASmote with encoder.

Every time a pulse is produced, a velocity measurement is obtained. We set the desired angular velocity to $2\pi/\mathrm{s}$, which means we can get about 128 measurement data per second. In one second, the robot transmits 10 packets to the base station. Each packet can contain maximum 28 measurements (15 in our implementation). When the data is received by the base station, it is forwarded to the central computer.

4.2. MASmote modelling, parameter estimation and measurement of velocity

The precise model of the servo motor used in MASmote is not available. Experiment shows that a highly nonlinear disturbance exists in the servo motors, as can be seen from Fig. 3, where 100 percent PWM input corresponds to 4.8 Volt. These kinds of nonlinearities also contribute to the disturbance on the rotary system on the robot. Approximately, the dynamic model of the servo motor can be obtained as a first order system like below:

$$w(s) = \frac{k}{\tau s + 1} v(s), \tag{14}$$

where w is the angular rate, v is the input voltage. The proportional constant k is estimated from static relationship between the input voltage and the output angular velocity of the servo motor, as shown in Fig. 3. The time constant τ is estimated from a step response of the servo motors. The constant k is estimated as k=0.35 and τ=0.12 seconds. In spite of some uncertainty in our estimated system model, our proposed adaptive compensator shows its robustness in the real experiments. One of our problem when using MASmote for our experiment is that the Timer component can only provide a time measurement with a minimal unit to 1 ms. This is not small enough to measure the time interval between two successive pulses produced by the encoder. While noticing that if the PWM signal is generated from Timer with a period of 20 ms, and we assume that the input clock

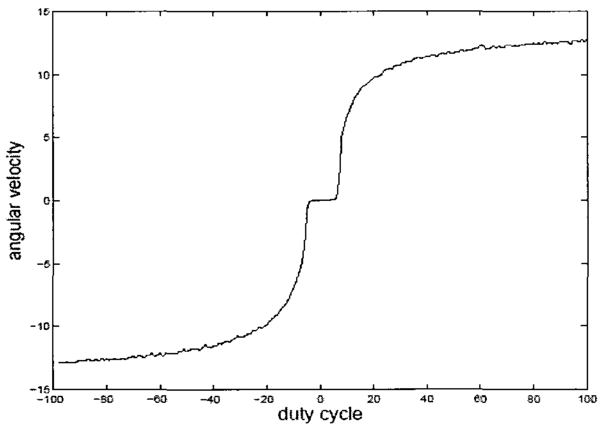


Fig. 3. Static nonlinearity and dead-zone of the servo motor on the MASmote.

for the Timer is 10^6 Hz; then at every period, the value of the Timer will go from 0 to 2×10^4 and go back to 0 gain. More accurate time stamps can be obtained by counting the periods of the Timer and direct access to Timer Count register. We choose 128 μs as the minimal measurement unit for the time interval measurement when using this method. This will introduce about 3 percent quantization error in measurement for the desired velocity.

5. EXPERIMENTAL RESULTS

The main challenging control objective is to maneuver the mobile robot to follow the desired trajectory with desired velocity as close as possible. However, there exists state-dependent disturbance torque in the rotating wheels of the mobile robots. The major sources for the disturbance torque are eccentricity, friction, gravitational force of the rotary system and nonlinearity of the servo motor. During the experiment, we have chosen the desired angular velocity as $w_d = 2\pi(\mathrm{rad/s})$ or 60 rpm. The desired position (angular) trajectory is $\theta(t) = 2\pi t$. For the open loop experiment, we have shown position-dependent disturbance on velocity output as depicted in Fig. 1. The output velocity signal has a mean of 6.2862 rad/s and a variance of 0.7563rad^2/s^2. Based on the dynamic model of the servo motor in (14), the modified servo dynamics is given by:

$$\dot{\theta}(t) = w(t), \tag{15}$$

$$J\dot{w}(t) = -a(\theta(t)) - \frac{w(t)}{T} + \frac{k}{T}v, \tag{16}$$

where T is the sampling time. Then, based on Theorem 1, the following simple control law is developed: $v = jT/k\tau'(t) + w(t)/k$ with $\tau'(t)=\hat{a}'(t) -(\alpha+\lambda)e_w(t) - \alpha\lambda\, e_\theta(t)$ where $\hat{a}'(t)$ is given in (12). For the periodic adaptation, the adaptation parameters were selected as: K=20/s^2, α =100/s, and $\lambda = 0.001/\mathrm{s}$. Fig. 4 shows the velocity signal after adaptive disturbance compensation in the state axis. It can be seen that the position-dependent disturbance is successfully eliminated. The remaining noise and fluctuation on the velocity measurement are due to the quantization noise, other non-ideality of the encoder, and unidentified speed-dependent disturbance like friction force. The effect caused by this kind of disturbance can be further relieved by high-level controllers. The velocity obtained has the mean of 6.2854 rad/s and the variance of 0.0859 rad^2/s^2. To compare the effectiveness of our adaptive compensator with traditional PI controller, in the following test, we set K=0 while keeping α and λ unchanged. Then the proposed adaptive controller is equivalent to the PI controller. Fig. 5 shows the result

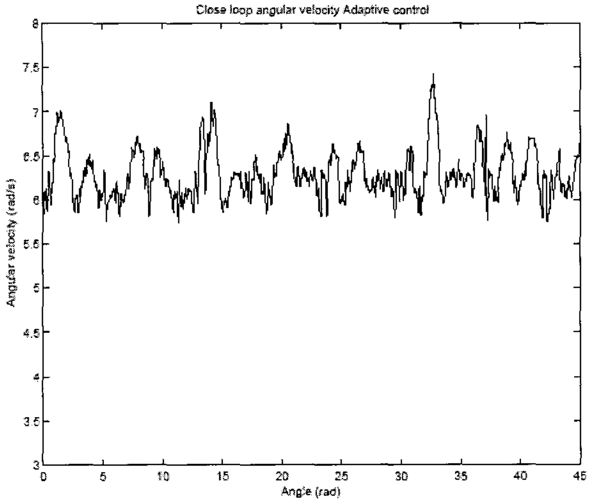


Fig. 4. Angular velocity of the wheel with periodic adaptive compensator on the state axis.

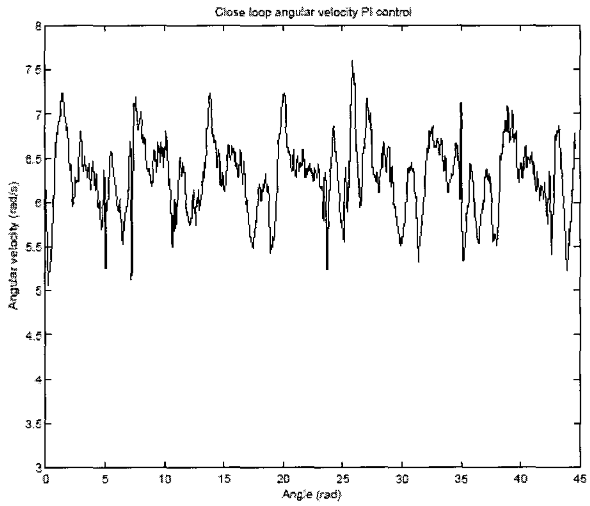


Fig. 5. Angular velocity of the wheel with PI controller on the state axis.

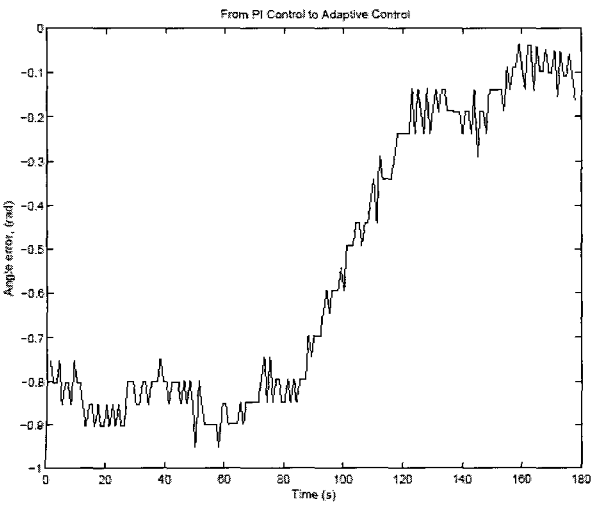


Fig. 6. Position error converges to zero under adaptive compensator.

of this PI controller. It is clear that simple PI controller can not compensate for the position-dependent disturbance effectively. There is still some position-dependent pattern caused by external disturbance in the output velocity signal. The mean of the output velocity is 6.2855 and the variance is 0.1873 rad^2/s^2. Another disadvantage of PI controller is that for both velocity and position tracking, it can not guarantee the asymptotic stability of the position error. In our experiment, the position error e_θ does not converge to zero, but has a steady value of about 0.5 rad. The proposed adaptive controller can achieve both velocity and position tracking. It can be seen in Fig. 6 that, if we change the PI controller to adaptive compensator by setting an appropriate value to K, the position error goes to zero asymptotically. The remaining error is due to the quantization error of the encoder and/or other unidentified disturbance.

6. CONCLUSIONS

In this paper, a state-dependent external disturbance of the wheeled-mobile robots was compensated using the state-periodic adaptive controller. The existing state-periodic adaptive compensator [5] was slightly modified for the actual application. From the experimental test, we found that the periodic disturbance of the wheeled-mobile robots was successfully eliminated. From the comparison with the traditional PI controller, the periodic adaptive controller showed a better performance.

REFERENCES

[1] Y. Q. Chen, K. L. Moore, and Z. Song, "Diffusion boundary determination and zone control via mobile actuator-sensor networks (MAS-net): Challenges and opportunities," *Proc. of SPIE's Defense and Security Symposium,* Orlando, FL, April 2004.

[2] C. C. de Wit and L. Praly, "Adaptive eccentricity compensation," *IEEE Trans. on Control Systems Technology*, vol. 8, no. 5, pp. 757-766, 2000.

[3] B. Friedland and S. Mentzelopoulou, "On adaptive friction compensation without velocity measurement," *Proc. of the First IEEE International Conference on Control Applications*, Dayton, OH, USA, pp. 1076-1081, Sep. 1992.

[4] A. Yazdizadeh and K. Khorasani, "Adaptive friction compensation based on the Lyapunov scheme," *Proc. of the IEEE International Conference on Control Applications*, Dearborn, MI, USA, pp. 1060-1065, Sep. 1996.

[5] H.-S. Ahn and Y. Q. Chen, "State-periodic adaptive friction compensation," *Proc. of the 16th IFAC World Congress*, Prague, Czech Republic, July 2005.

[6] S.-H. Han, Y.-H. Kim, and I.-J. Ha, "Iterative

identification of state-dependent disturbance torque for high-precision velocity control of servo motors," *IEEE Trans. on Automatic Control*, vol. 43, no. 5, pp. 724-729, 1998.

[7] H. Du and S. S. Nair, "Low velocity friction compensation," *IEEE Control Systems Magazine*, vol. 18, no. 2, pp. 61-69, 1998.

[8] A. T. Zaremba, I. V. Burkov, and R. M. Stuntz, "Active damping of engine speed oscillations based on learning control," *Proc. of the American Control Conference*, Philadelphia, PA, USA, pp. 2143-2147, June 1998.

[9] C. C. de Wit, "Control of systems with dynamic friction," *Proc. of CCA'99 Workshop on Friction*, Hawaii, USA, Aug. 1999.

[10] H.-S. Ahn, Y. Q. Chen, and H. Dou, "State-periodic adaptive compensation of cogging and Coulomb friction in permanent-magnet linear motors," *IEEE Trans. on Magnetics*, vol. 41, no. 1, pp. 90-98, 2005.

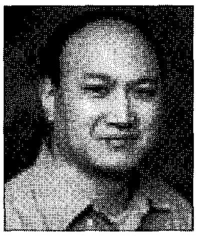
[11] Jr D. A. Haessig and B. Friedland, "On the modeling and simulation of friction," *Proc. of the American Control Conference*, San Diego, CA, USA, pp. 1256-1261, May 1990.

[12] C. C. de Wit and L. Praly, "Adaptive eccentricity compensation," *Proc. of the 37th IEEE Conference on Decision and Control*, Tampa, Florida, pp. 2271-2276, Dec. 1998.

[13] Z. Wang, Z. Song, P.-Y. Chen, A. Arora, K. L. Moore, and Y. Q. Chen, "Masmote-a mobility node for MAS-net (mobile actuator sensor networks)," *Proc. of the IEEE International Conference on Robotics and Biomimetics*, Shengyang, China, pp. 816- 821, Aug. 2004.

[14] H.-S. Ahn, Y. Q. Chen, and Z. Wang, "State-dependent disturbance compensation in low-cost wheeled mobile robots using periodic adaptation," *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Alberta, Canada, pp. 729-734, Aug. 2005.

Hyo-Sung Ahn received the B.S. and M.S. degrees in Astronomy and Space Science from Yonsei University, Seoul, Korea, in 1998 and 2000, and M.S. and Ph.D. degrees in Electrical Engineering from University of North Dakota and Utah State University, USA, in 2003 and 2006 respectively. He is with Intelligent Robot Research Division of Electronics and Telecommunications Research Institute (ETRI), Korea. His research interests include learning control, periodic adaptive learning control, wireless sensor network, indoor localization, inertial navigation system, distributed control system, parametric interval computation, and intelligent robotics. He is the leading author of a research monograph "Iterative Learning Control: Robustness and Monotonic Convergence for Interval Systems" (with Kevin L. Moore and YangQuan Chen, ISBN: 978-1-84628-846-3, Communications and Control Engineering Series, Springer, 2007).



YangQuan Chen received the B.S. degree in Industrial Automation from the University of Science and Technology of Beijing (USTB) in 1985, the M.S. degree in Automatic Control from Beijing Institute of Technology (BIT) in January 1989, and the Ph.D. degree in Control and Instrumentation, Nanyang Technological University (NTU), Singapore, in July 1998. He is currently an Assistant Professor of Electrical and Computer Engineering at Utah State University and the Acting Director of the Center for Self-Organizing and Intelligent Systems (CSOIS). His current research interests include identification and control of distributed parameter systems with networked movable actuators and sensors, autonomous ground and aerial mobile robots, and fractional order dynamic systems and control.

Wonpil Yu is with Intelligent Robot Research Division, ETRI, where his current jobs are developing image processing algorithms for mobile information processing applications and indoor location sensing methods for mobile robots. Prior to joining ETRI in 2001, he worked for ADD at Daejeon, Korea, where he was involved in the development of a precision stabilizer for radar seeker system. During that period, his main job was development of multiprocessor-based signal processing algorithms and implementation. He received the B.S. degree in Control and Instrumental Engineering from Seoul National University, Seoul, Korea in 1992 and the M.S. and Ph.D. degrees in Electrical Engineering from KAIST, Daejeon, Korea in 1994 and 1999, respectively. His areas of research include robot vision, image processing, and robot navigation.