An Adaptive Control Method for the Linear Switched Reluctance Motor Based on DSP

Jin-quan Li[1], Norbert.C.Cheung[2], J.F.Pan[1], Guang-zhong Cao[1]

1 College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, P.R.China
2 Electrical Engineering Department, Hong Kong Polytechnic University, Hong Kong, P.R.China

Abstract-The linear switched reluctance motor (LSRM) is a new kind of direct-drive actuator, however, it is very difficult to build an exact theoretic model for the LSRM. In this paper, an indirect self-tuner is proposed for position control of the LSRM by combining the recursive least squares (RLS) estimator with the minimum-degree pole placement method (MDPP) for controller design. Control system construction and operation based on one single Digital Signal Processor (DSP) are also established. Experimental results demonstrate the control scheme with on-line least-square parameter identification has a better performance than PID controller on modifying steady-error variances between each operation side in square-wave tracking. Experimental results prove that the control algorithm considering disturbances has smaller steady-state error compared with PID control algorithm.

Keywords–Switched reluctance, on-line identification, least-square, pole-placement, DSP

I. INTRODUCTION OF THE LSRM

The construction of the LSRM is shown in Fig. 1. The three-phase LSRM has a configuration with an active (with windings) translator and a passive (without windings) stator [1]. The translator and stator are both laminated with 0.5 mm silicon-steel plates. So the machine has lower eddy current losses as the flux is in the same direction as lamination. A 1μm resolution linear optical encoder is integrated in the LSRM system to observe the motion profile of the moving translator and provide feedback position information. The mechanical parameters of the LSRM are listed in Table 1.

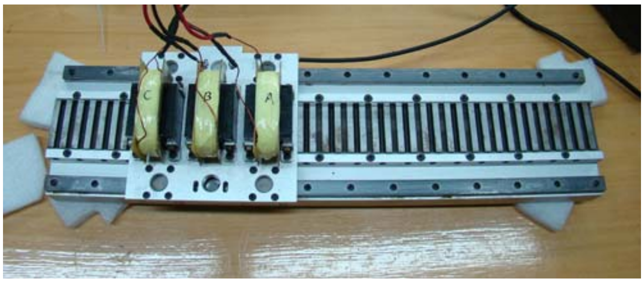


Fig. 1: Construction of the LSRM

Table 1: Specifications of the LSRM

Parameters	Value
Mass of translator	3 Kg
Mass of stator	17 Kg
Motor length	120 mm
Pole width	6 mm
Slot width(z)	6 mm
Encoder accuracy	1μm
Air gap width(z)	0.4 mm

II. MODELING OF THE LSRM

The LSRM has a highly nonlinear characteristic due to its nonlinear flux behavior. An elementary equivalent circuit for the LSRM can be derived neglecting the mutual inductance between the phases. The fundamental principles of the LSRM are the voltage balancing equations. The applied voltage to one phase is equal to the sum of the resistive drop and the rate of the flux-linkages given as [1],

$$V = R_s i + \frac{d\lambda(x,i)}{dt} \tag{1}$$

where R_s is the resistance per phase, x is displacement, and λ is the flux linkage per phase given by,

$$\lambda = L(x,i)i \tag{2}$$

where L is the inductance dependent on translator position and phase current. The phase voltage equation can be expressed as,

$$V = R_s i + L(x,i)\frac{di}{dt} + i\frac{dx}{dt}\cdot\frac{dL(x,i)}{dx} \tag{3}$$

The force command of translator is expressed as,

$$f(i_a(t), i_b(t), i_c(t), x(t)) = \sum_{k=a}^{c} \frac{\partial \int_0^{i_k(t)} \lambda_k \cdot d\tau_k(t)}{\partial x(t)}$$

$$= M\frac{d^2x(t)}{dt^2} + Bv\frac{dx(t)}{dt} + f_l(t) \tag{4}$$

where f is the generated electromagnetic force, $f_l(t)$ is the external load force, M and B are the mass and friction constant, respectively. So the LSRM is a second-order system and the model can be expressed as,

$$A(q^{-1})y(t) = B(q^{-1})u(t) + e(t) \tag{5}$$

where

$$\begin{cases} A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} \\ B(q^{-1}) = b_0 q^{-1} + b_1 q^{-2} \end{cases} \tag{6}$$

$y(t)$ represents the position feedback of the LSRM. $u(t)$ is the generated electromagnetic force [1]. The goal is to identify the value of a_1, a_2, b_0 and b_1.

III. LEAST SQUARE METHOD WITH EXPONENTIAL FORGETTING

Several recursive estimation methods can be used to estimate the coefficients of polynomials. In this paper, the recursive least-squares estimation algorithm [3] is applied. The process model (5), can be written explicitly as,

$$y(t) = \varphi^T(t-1)\theta \tag{7}$$

where

$$\begin{cases} \theta^T = (a_1\ a_2\ b_0\ b_1) \\ \varphi^T(t-1) = \big(-y(t-1)\ -y(t-2)\ u(t)\ u(t-1)\big) \end{cases} \tag{8}$$

The least-squares estimator with exponential forgetting is given by,

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\varepsilon(t) \tag{9}$$

$$\varepsilon(t) = y(t) - \varphi^T(t-1)\hat{\theta}(t-1) \tag{10}$$

$$K(t) = P(t-1)\varphi(t-1)\big(\lambda + \varphi^T(t-1)P(t-1)\varphi(t-1)\big)^{-1} \tag{11}$$

$$P(t) = \big(I - K(t)\varphi^T(t-1)\big)P(t-1)/\lambda \tag{12}$$

where P is the covariance matrix and λ is forgetting factor. *K(t)* can be interpreted as the adjusting gain. If *K(t)*=0, the estimated parameter θ converges to some constants. The forgetting factor, which can be given from 0 to 1, reflects the parameter converging rate. If the forgetting factor is set at a small value, the estimated parameters would converge quickly with big ripples. On the other hand, when the forgetting factor is given a big value, the estimated parameters would converge slowly with small ripples. The initial covariance matrix *P(0)* is selected as rI, which is a *4-th* unit matrix scaled by a positive scalar r, r is given as a big value for initial estimation.

If the input signal to the process is sufficiently exciting and the structure of the estimated model is compatible with the process, the estimated coeffcients will converge to their real values. The flow chart of real-time parameter estimations are shown in Fig. 2.

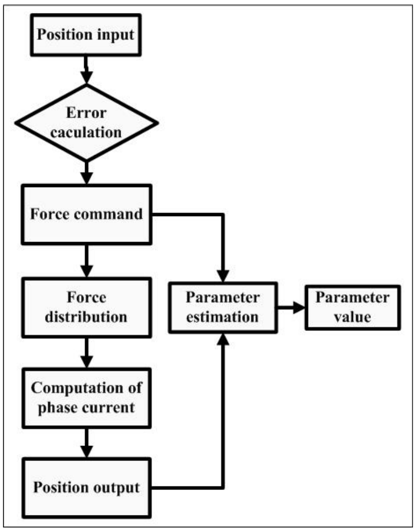


Fig. 2: The flow chart of real-time parameter estimations

IV. POLE PLACEMENT DESIGN

Pole placement design [2] is a simple method for controller design. The idea is to determine a controller that gives desired closed-loop poles.

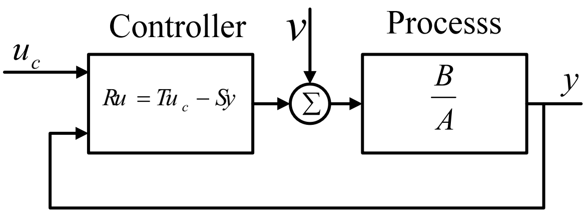


Fig. 3: The control system for LSRM

As shown in Fig. 3, it is assumed that the controller for the LSRM can be described by,

$$Ru(t) = Tu_c(t) - Sy(t) \tag{13}$$

where

$$\begin{cases} R = 1 + rq^{-1} \\ S = s_0 + s_1 q^{-1} \end{cases} \tag{14}$$

Elimination of $u(t)$ between (6), and (13), gives the following equations for the closed-loop system,

$$y(t) = \frac{BT}{AR+BS}u_c(t) \tag{15}$$

$$u(t) = \frac{AT}{AR+BS}u_c(t) \tag{16}$$

The closed-loop characteristic polynomial is thus expressed as,

$$AR + BS = A_c = A_0 A_m \tag{17}$$

where

$$\begin{cases} A_0(q^{-1}) = 1 + a_0 q^{-1} \\ A_m(q^{-1}) = 1 + a_{m1}q^{-1} + a_{m2}q^{-2} \end{cases} \tag{18}$$

The key idea of the design method is to specify the desired closed-loop characteristic polynomial A_c.

A controller design with no cancellation of process zero is applied. The desired closed-loop transfer operator is,

$$H_m(q^{-1}) = \beta\frac{b_0 + b_1 q^{-1}}{1 + a_{m1}q^{-1} + a_{m2}q^{-2}} \tag{19}$$

where

$$\beta = \frac{1 + a_{m1} + a_{m2}}{b_0 + b_1} \tag{20}$$

and β is the unit steady state gain. Equation (17) becomes,

$$\begin{aligned} &(1 + a_1 q^{-1} + a_2 q^{-2})(1 + rq^{-1}) + (b_0 + b_1 q^{-1})(s_0 + s_1 q^{-1}) \\ &= (1 + a_{m1}q^{-1} + a_{m2}q^{-2})(1 + a_0 q^{-1}) \end{aligned} \tag{21}$$

Solving for r, s_0 and s_1, we can get,

$$r = \frac{a_0 a_{m2} b_0^2 + (a_2 - a_{m2} - a_0 a_{m1}) b_0 b_1}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} + \frac{(a_0 + a_{m1} - a_1) b_1^2}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} \tag{22}$$

$$s_0 = \frac{b_1 (a_0 a_{m1} - a_2 - a_{m1} a_1 + a_1^2 + a_{m2} - a_1 a_0)}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} + \frac{b_0 (a_{m1} a_2 - a_1 a_2 - a_0 a_{m2} + a_0 a_2)}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} \tag{23}$$

$$s_1 = \frac{b_1 (a_1 a_2 - a_{m1} a_2 + a_{m2} a_0 - a_2 a_0)}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} + \frac{b_0 (a_{m2} a_2 - a_2^2 - a_0 a_{m2} a_1 + a_0 a_{m1} a_2)}{b_1^2 - a_1 b_0 b_1 + a_2 b_0^2} \tag{24}$$

In order to make the error equal to zero, the following condition should hold as,

$$\frac{BT}{AR + BS} = \frac{BT}{A_c}, T = \beta A_0 = \beta (1 + a_0 q^{-1}) \tag{25}$$

V. AN IMPROVED DESIGN PROCEDURE

The pole placement procedure can be modified to take disturbances into account [2]. For simplicity we will assume that disturbance v occurs at of the process input as shown in Fig. 3. This can be calculated by assuming that the disturbance v is generated by the dynamic system as,

$$A_d v = e \tag{26}$$

where e stands for white noise. A step disturbance is generated in a discrete-time system by,

$$A_d(q^{-1}) = 1 - q^{-1} \tag{27}$$

The system described in Fig.2 can be expressed as,

$$y(t) = \frac{BT}{AR + BS} u_c(t) + \frac{BR}{A_d (AR + BS)} e(t) \tag{28}$$

$$u(t) = \frac{AT}{AR + BS} u_c(t) - \frac{BS}{A_d (AR + BS)} e(t) \tag{29}$$

According to the characteristics of Diophantine equation, if R and S are solutions to (17), it follows that,

$$\begin{cases} R^0 = XR + YB \\ S^0 = XS - YA \end{cases} \tag{30}$$

and satisfies the equation,

$$AR^0 + BS^0 = XA_c \tag{31}$$

X is assumed according to (27) that,

$$X(q^{-1}) = 1 + x_0 q^{-1} \tag{32}$$

Y can be obtained form (32) and (30) as,

$$Y = y_0 = -\frac{(1 + x_0)(1 + r)}{b_0 + b_1} \tag{33}$$

$$T^0 = TX \tag{34}$$

Then a new controller can be obtained as,

$$R^0 u = T^0 u_c - S^0 y \tag{35}$$

VI. EXPERIMENTAL IMPLEMENTATION

The experimental setup is shown in Fig. 4. The computer is used to target code into a DSP. The index of DSP is TMS320F2812 from TI Company. It contains four Digtial-to-Analog(DA) converters and two enhanced quadrature encoder pulse (QEP) modules. The current driver consists of three DA input with 90 VDC voltage supplier. In the experiment, the LSRM system is considered as a second-order system with a sampling time of 0.001 s. Assuming that $a_{m1} = -1.935$, $a_{m2} = 0.938$, $a_0 = -0.9$ and $x_0 = -0.8$ and a forgetting factor of $\lambda = 0.99$ has been introduced. The software flow chat of DSP is shown in Fig. 5.

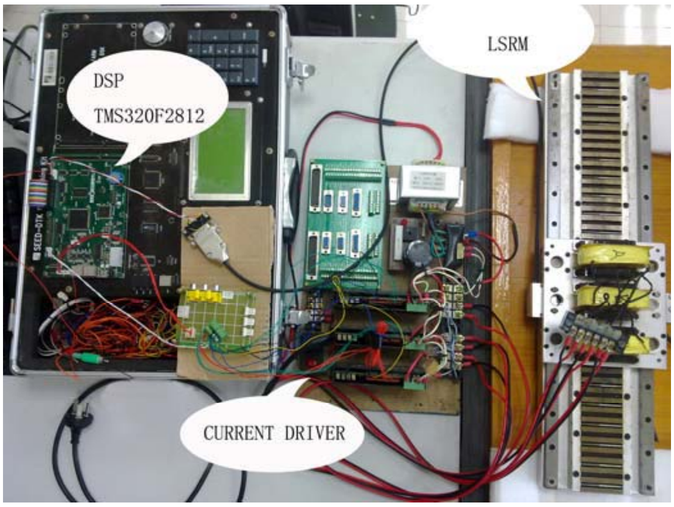


Fig. 4: The experimental setup

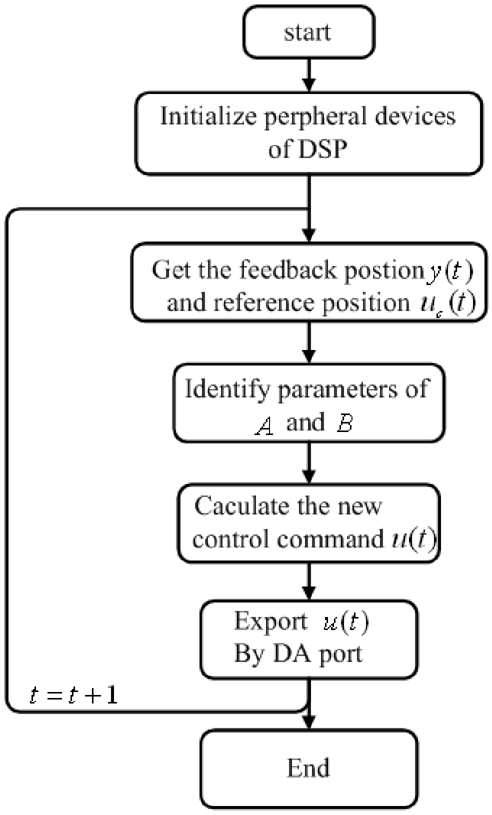
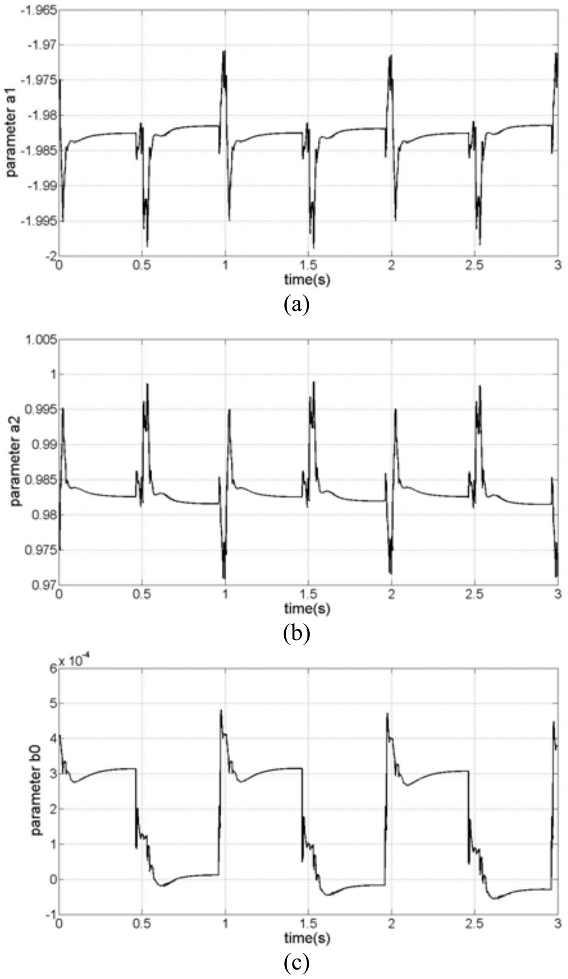


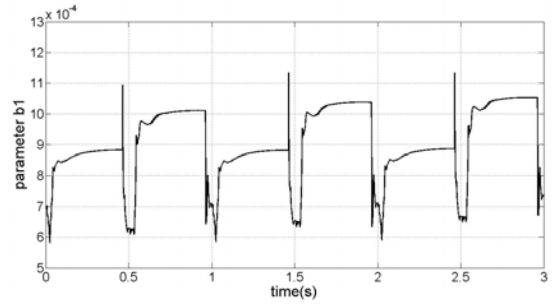
Fig. 5: The software flow chat of DSP



(a)

(b)

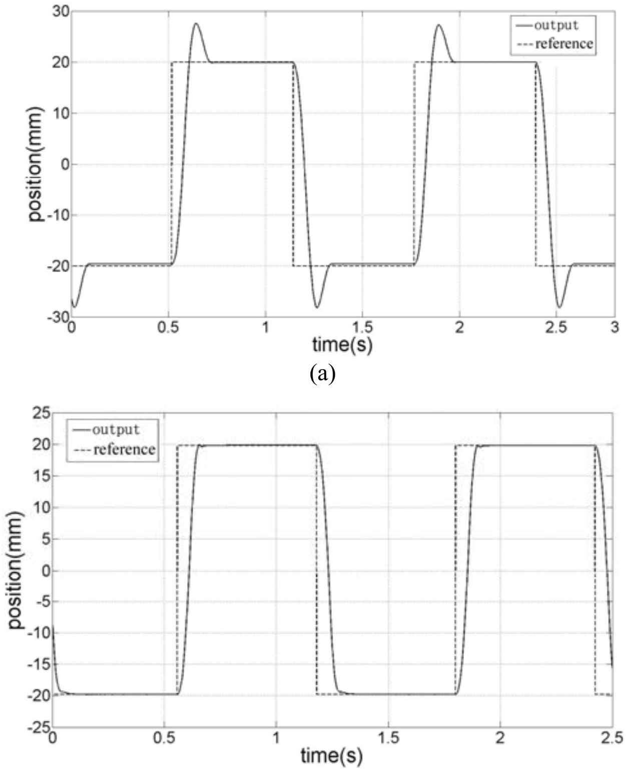
(c)



(d)

Fig. 6: Parameter estimation of (a)a1,(b)a2,(c)b0,(d)b1

Fig. 6 shows the parameter estimating of the LSRM system. The figure shows that parameters a_1, a_2, b_0 and b_1 can converge to their stable values with small variations.

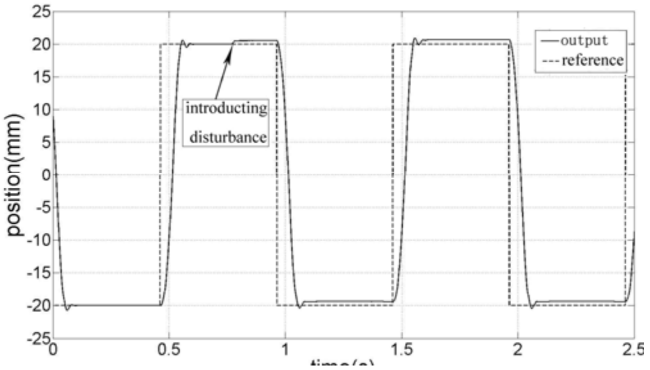


(a)

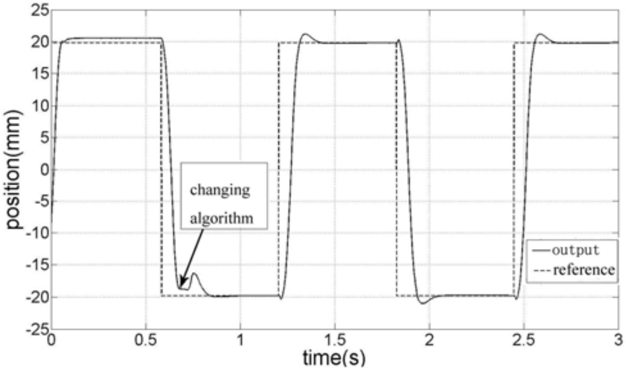
(b)

Fig. 7: Response of square-wave command (a)PID control algorithm (b)adaptive control algorithm without considering disturbances

According to Fig. 7, it can be found that the state-error between two sides in square-wave tracking is obviously different under PID control algorithm and adaptive algorithm without considering disturbances has a better dynamic performance.



(a)



(b)

Fig. 8: Disturbance response of adaptive control algorithm (a) without considering disturbances (b) considering disturbances

A step disturbance is introduced into the system at 0.7s as shown in Fig. 8 (a). It can be found that the steady-state error is larger when disturbance is added, and the control algorithm without considering disturbances can not keep steady-state error as the same level as before. The control algorithm considering disturbances is introduced to replace the control algorithm without considering disturbances. As shown in Fig. 8 (b), it can be found that the state-error after the replacement become smaller. Therefore, the adaptive algorithm considering disturbance influence has more robustness.

VII. CONCLUSION

This paper proposed an adaptive control method for the LSRM position control system. Control system construction and operation based on one single Digital Signal Processor (DSP) are also established. Experimental results demonstrate the control scheme with on-line least-square parameter identification has a better performance than PID controller on modifying steady-error variances between two sides in square-wave tracking. The disturbances that act on the process are also calculated in pole placement procedure. Experimental results prove that the control algorithm considering disturbances has stronger ability to restrain disturbances.

ACKNOWLEDGMENT

The authors would like to thank the National Natural Science Foundation of China and Guangdong Natural Science Fund under the project code 51007059 and 2008225, the authors would also like to thank Shenzhen government fund under the project code JC201005280390A and Hong Kong Polytechnic University under the project code G-YX2Q for the support.

REFERENCE

[1] T.J.E. Miller, “Switched reluctance motor and their control [M]”, Magnet Physics Publishing and Clarendon Press, Oxford, 1993.

[2] K.J. Åström and B. Wittenmark, “Adaptive Control”, Addison-Wesley, 1995.

[3] Lennart Ljung. “System Identification—Theory for the User[M]”. Prentice-Hall.

BIOGRAPHY

Jin-quan Li was born in Henan, China, in 1985. He received the B.S. degree in automation from Shenzhen University, Shenzhen, China, in 2009. Currently he is studying at College of Mechatronics and Control Engineering, Shenzhen University. His main research interest is advanced control methods.

N. C. Cheung received the B.Sc. degree from the University of London, London, U.K., the M.Sc. degree from the University of Hong Kong, Hong Kong, and the Ph.D. degree from the University of New South Wales, Sydney, Australia, in 1981, 1987, and 1995, respectively. He is currently with the Department of Electrical Engineering, Hong Kong Polytechnic University, Hong Kong. His research interests are motion control, actuator design, and power electronic drive.

J.F. Pan graduated from Department of Electrical Engineering of Hong Kong Polytechnic University in Hong Kong for the Ph.D. degree in 2006. Currently he is working in College of Mechatronics and Control Engineering, Shenzhen University. His main research interests are design and control of switched reluctance motors and generators.

Guang-zhong Cao obtained the B.S., M.S. degree and the Ph.D. degree in electrical engineering and automation from Xi'an Jiaotong University, Shanxi Procince,China. He is now a professor in the College of Mechatronics and Control Engineering, Shenzhen University. And also he is currently the senior director of Shenzhen University - USA TI embedded control Joint Laboratory. He has published over 60 papers in refereed journals and conferences. His research interest are embedded systems, motor control, data acquisition units and DSP hardware/software architectures, computer applications in industry, transducer techniques and automatic detection systems.