Research Journal of Applied Sciences, Engineering and Technology 6(17): 3187-3192, 2013
DOI:10.19026/rjaset.6.3622
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: January 14, 2013 Accepted: February 22, 2013 Published: September 20, 2013

Research Article

Sliding Mode Control with Nonlinear Disturbance Observer Based on Genetic Algorithm for Rotary Steering Drilling Stabilized Platform

Yuantao Zhang
School of Electrical and Information Engineering, Chongqing University of Science and Technology, Chongqing 401331, China, Tel.: 86-13996010839

Abstract: This study proposed a novel robust sliding mode control strategy for the stabilized platform of rotary steering drilling system. Firstly, a Nonlinear Disturbance Observer (NDO) which can converge exponentially with suitable design parameters is used to observe the uncertain disturbance of stabilized platform under work condition. Subsequently, sliding mode controller is designed to guarantee the robustness of the closed-loop system. The adaptive rate of switching gain is designed and sign function is replaced by bipolar sigmoid function to weaken chattering. Finally, Genetic Algorithm (GA) is applied to search the optimal controller parameters, including switching function coefficient, switching gain adaptive coefficient, sigmoid function coefficient and observer coefficient. Simulation results show that NDO can observe the uncertain disturbance effectively, controller output is decreased and stabilized platform can get optimal control performance and robustness.

Keywords: Genetic algorithm, nonlinear disturbance observer, Stabilized platform, rotary steering drilling system, sliding mode control

INTRODUCTION

Rotary steering drilling technology, which is currently widely used in oil and gas exploration, can achieve accurate automatic control of well trajectory of horizontal well, extended reach well, branch well and other complex wells. The key technology is the control problem of stabilized platform, for the control performance will directly affect exploration efficiency. It requires the stabilized platform of rotary steering drilling tool has rapid large angle attitude change, high control accuracy, good robustness and adaptability (Geoff, 2000). However, due to the influences of strong nonlinearity, uncertainty and time-variant parameters under work condition, stabilized platform is unable to obtain satisfactory static and dynamic performance and robustness is also poor. Therefore, with the development of nonlinear control and intelligent control technologies, many researchers begin to study the robust control problem of stabilized platform with some advanced control strategies (Li *et al*., 2010; Huo *et al*., 2010a; Xue *et al*., 2010; Zhang *et al*., 2012; Huo *et al*., 2010b; Cui *et al*., 2007).

Sliding mode control is a common robust control strategy for uncertain nonlinear system. Nowadays, many researchers begin to study the sliding mode control problem of stabilized platform (Zhang *et al*., 2012; Huo *et al*., 2010b; Cui *et al*., 2007). But the problem lies that the system uncertain upper bound must be known, while the actual upper bound generally cannot be measured, so sliding mode control is usually combined with other methods (Fei and Ding, 2012; Yeh, 2012).

Nonlinear disturbance observer technology is an effective method to process unknown disturbances and nonlinear system uncertainties in recent years. Its principle is to take uncertain factors of system unknown disturbances and unmodeled dynamics uniformly as system composite disturbance and then apply disturbance observer to estimate the disturbance. Nowadays nonlinear disturbance observer technology has become a research hotspot in the field of nonlinear control system (Zhi and Cai, 2012; Liu *et al*., 2011; Noh *et al*., 2012).

Genetic Algorithm (GA), which is widely used in complex system optimization design, is an adaptive probability optimization technology based on genetic and evolutionary mechanism. In order to obtain optimal control performance, many researchers recently begin using genetic algorithm for optimal design of controller parameters (Chen *et al*., 2011; Rani *et al*., 2012; Douiri *et al*., 2012).

In this study, a nonlinear disturbance observer is used to observe the uncertain disturbance of stabilized platform under work condition and then sliding mode controller is designed to guarantee the robustness of the closed-loop system. In order to get optimal control performance and robustness, genetic algorithm is finally applied to search the optimal controller parameters. Simulation results verify the effectiveness of the algorithm.

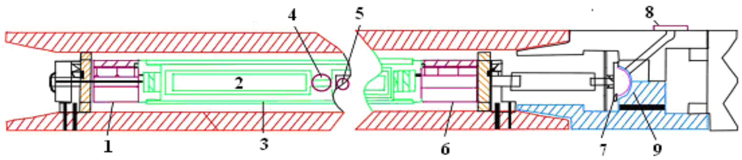

Fig. 1: Structure of stabilized platform

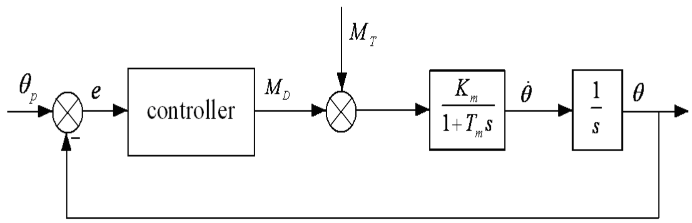

Fig. 2: Structure of control model of stabilized platform

SYSTEM DESCRIPTION

Rotary steering drilling stabilized platform is composed of upper turbo-dynamotor, lower turbo-dynamotor, electronic control unit, upper plate valve and lower plate valve (Fig. 1). Upper turbo-dynamotor provides power for electronic control unit. Lower turbo-dynamotor is a variable torque generator. Electronic control unit is a detection and control component. Linear accelerometer is used to detect tool face angle and deviation angle of stabilized platform and rate gyro is used to detect rotation trend and angular velocity of stabilized platform in electronic control unit. Look from top to bottom, upper turbo-dynamotor rotates clockwise, while lower turbo-dynamotor rotates counterclockwise and rotary table drive tool shell and lower plate valve rotate clockwise. The torque of lower turbo-dynamotor must balance the torques of upper turbo-dynamotor, lower and upper plate valve and rotary friction. The torque of upper turbo-dynamotor is small and can be considered as constant and the other torques are variable under work condition. In order to achieve steerable drilling, it only needs to control the torque of lower turbo-dynamotor to make the upper plate valve driven by stabilized platform stable to the preset tool face angle.

The stabilized platform of rotary steering drilling tool is a SISO system and it can be seen as generator-style single-axis inertial stabilized platform. Figure 2 shows the structure of control model of stabilized platform.

In Fig. 2, The transfer function of lower turbo-dynamotor is $K_m(1 = T_m^s)^{-1}$, where $T_m = J/f$, $K_m = 1/f$ and J is platform moment of inertia, f is platform rotation friction coefficient. M_D is output torque of lower turbo-dynamotor. M_T denotes total disturbance torque, including electromagnetic torque of upper turbo-dynamotor, bearing friction torque, viscous friction torque of rotary drilling fluid and friction torque of disc valve system on platform. θ and $\dot{\theta}$ is tool face angle and tool face angular velocity of platform, respectively.

Choose $x = [x_1, x_2]^T = [\theta, \dot{\theta}]^T$ as state variables and y = θ = x1 as output variable. The uncertain nonlinear mathematical model of platform is (Zhang *et al*., 2012):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + bu + F \\ y = x_1 \end{cases} \tag{1}$$

In formula (1), $f(x) = -\frac{1}{T_m} x_2$, $b = \frac{K_m}{T_m}$

$$\begin{aligned} F &= \frac{K_m}{T_m} M_T \\ &= \frac{K_m}{T_m} \Big\{ M_U + 0.05\mu(n_0 - x_2 \frac{30}{\pi}) \operatorname{sgn}(n_0 - x_2 \frac{30}{\pi}) + \\ &\quad 23.29 \operatorname{sgn}(n_0 - x_2 \frac{30}{\pi})(0.008 \sin DEV + 0.02 \cos DEV \Big\} \end{aligned}$$

where, M_U is output torque of upper turbo-dynamotor, μ is mud viscosity coefficient, n_0 is drill pipe speed and DEV is deviation angle. F denotes the total uncertain disturbance.

CONTROLLER DESIGN

The control object of stabilized platform is to make output tool face angle tracking set angle. Due to the influence of uncertain disturbance, the control output will be large while designing sliding mode controller to system (1) directly. Therefore, nonlinear disturbance observer is used to observe the uncertain disturbance

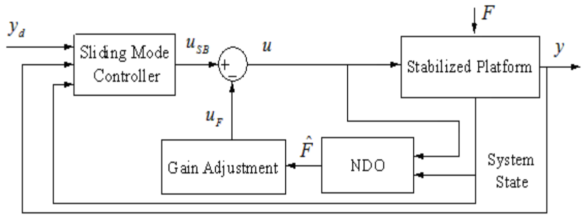

Fig. 3: Structure of sliding mode controller based on NDO

firstly and then the unobserved part is compensated by sliding mode controller. The system control structure is shown as Fig. 3.

Nonlinear disturbance observer: The nonlinear disturbance observer can be described as follow (Zhi and Cai, 2012):

$$\begin{cases} \hat{F} = z + p(x_1, x_2) \\ \dot{z} = -L(x_1, x_2)z + L(x_1, x_2)\cdot \\ \quad [-p(x_1, x_2) - f(x) - bu] \end{cases} \tag{2}$$

where, $p(x_1, x_2)$ is designed nonlinear function and $L(x1, x_2)$ is observer gain which satisfies:

$$L(x_1, x_2)\dot{x}_2 = dp(x_1, x_2)/dt \tag{3}$$

Define observation error is:

$$\tilde{F} = F - \hat{F} \tag{4}$$

Differential prior knowledge of Fis often unknown, so hypothesize disturbance change is slow relative to the observer's dynamic characteristic, that is:

$$\dot{F} = 0 \tag{5}$$

Considering formula (2) and (5), the observer error dynamic equation is:

$$\begin{aligned} \dot{\tilde{F}} &= \dot{F} - \dot{\hat{F}} = -\dot{z} - \dot{p}(x_1, x_2) = L(x_1, x_2)[z + \\ & p(x_1, x_2)] - L(x_1, x_2)[\dot{x}_2 - f(x) - bu] = \\ & L(x_1, x_2)\hat{F} - L(x_1, x_2)F = -L(x_1, x_2)\tilde{F} \end{aligned} \tag{6}$$

Formula (6) shows that the observation error can converge exponentially by proper choosing $L(x_1, x_2)>0$.

Choose $L(x_1, x_2) = \alpha$, α, is a positive constant namely observer coefficient, design:

$$p(x_1, x_2) = ax_2 \tag{7}$$

The NDO output is sent to gain adjustment module and the observed disturbance are converted to the control variable of corresponding input channel. From system (1) we can get:

$$\dot{x}_2 = f(x) + b(u + \hat{F}/b) \tag{8}$$

Thus gain is 1/b and:

$$u_F = \hat{F}/b \tag{9}$$

Sliding mode controller: With the introduction of NDO, the second subsystem of system (1) can be described as:

$$\begin{aligned} \dot{x}_2 &= f(x) + bu + F = f(x) + b(u_{SB} - u_F) + F = \\ & f(x) + bu_{SB} - \hat{F} + F = f(x) + bu_{SB} + \tilde{F} \end{aligned} \tag{10}$$

Formula (10) shows that the system disturbance changed from F to $\tilde{F}$ with NDO and the total disturbance is decreased, so system (1) can be expressed as formula (11):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + bu_{SB} + \tilde{F} \\ y = x_1 \end{cases} \tag{11}$$

Now design sliding mode controller to system (11). Define tracking error as $e = y - y_d = x_1 - y_d$ and design switching function as s = ce = $\dot{e}$ (cis positive constant namely switching function coefficient), then:

$$\dot{s} = c\dot{e} + \ddot{e} = c\dot{e} + f(x) + bu_{SB} + \tilde{F} - \ddot{y}_d \tag{12}$$

Hypothesize observation error $\tilde{F}$ is bounded and unknown and $|\tilde{F}| < \delta$. Design control law as follow:

$$u_{SB} = \frac{1}{b}\left[-f(x) + \ddot{y}_d - c\dot{e} - \hat{\delta}\varphi(h,s)\right] \tag{13}$$

where, $\hat{\delta}$ is the estimated value of δ and φ(h, s) is bipolar sigmoid function. As we know, using bipolar sigmoid function to replace sign function can effectively weaken chattering of sliding mode control (Ding *et al*., 2012; Zhao *et al*., 2011).

Define $\tilde{\delta}$= δ - $\hat{\delta}$and parameter adaptive law is:

$$\dot{\hat{\delta}} = \lambda |s| \tag{14}$$

where, α is a positive constant namely switching gain adaptive coefficient.

φ(h, s) can be described as:

$$\varphi(h,s) = (1 - e^{-hs})/(1 + e^{-hs}) \tag{15}$$

where, h is called sigmoid function coefficient and h>1. Figure 4 shows the change of φ(h, s) with different h.

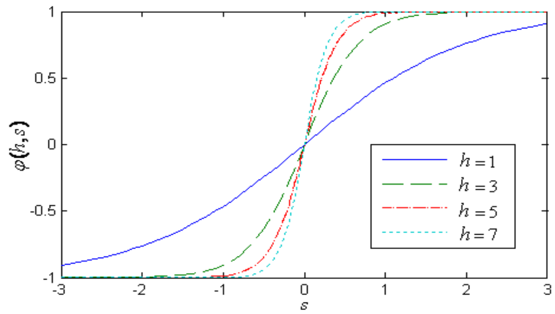

Fig. 4: Bipolar sigmoid function

Stability analysis: For the whole closed-loop system, design Lypunov function as follow:

$$V = \frac{1}{2}s^2 + \frac{1}{2\lambda}\tilde{\delta}^2 + \frac{1}{2}\tilde{F}^2 \tag{16}$$

Differentiate V and bring control law (12) and adaptive law (13) into the result.

$$\begin{aligned}
\dot{V} &= s\dot{s} - \tilde{\delta}\dot{\hat{\delta}}/\lambda + \tilde{F}\dot{\tilde{F}} \\
&= s\left(c\dot{e} + \ddot{e}\right) - \tilde{\delta}\dot{\hat{\delta}}/\lambda + \tilde{F}\left[-L(x_1,x_2)\tilde{F}\right] \\
&= s\left(c\dot{e} + f(x) + bu_{SB} + \tilde{F} - \ddot{y}_d\right) - \tilde{\delta}\dot{\hat{\delta}}/\lambda - L(x_1,x_2)\tilde{F}^2 \\
&= s(-\hat{\delta}\varphi(h,s) + \tilde{F}) - \tilde{\delta}\dot{\hat{\delta}}/\lambda - L(x_1,x_2)\tilde{F}^2 \\
&\le -\hat{\delta}|s| + \delta|s| - \tilde{\delta}|s| - L(x_1,x_2)\tilde{F}^2 \\
&= -L(x_1,x_2)\tilde{F}^2 \\
&= -a\tilde{F}^2
\end{aligned} \tag{17}$$

For observer coefficient $\alpha>0$, thus $\dot{V}\le 0$.

GENETIC OPTIMIZATION

The designed sliding mode controller based on nonlinear disturbance observer can achieve robust control of stabilized platform tool angle. But because the parameters of sliding mode controller, including switching function coefficient c, switching gain adaptive coefficient λ, sigmoid function coefficient h and observer coefficient α, are designed by experience, so the control performance and robustness cannot achieve optimization. Therefore, optimization calculation is necessary to get optimal controller parameters. Genetic algorithm is a natural evolutionary process by simulating random, adaptive searching optimal solution method. In this study, genetic algorithm is applied as the optimization method for controller parameters.

The optimization evidence in optimization search of genetic algorithm is called objective function. The design of objective function has much to do with the performance of genetic algorithm. In order to make the dynamic characteristics meet the requirement and improvement and avoid excessive control variable happening, the objective function is chosen as follow:

$$J = a_1\sum e^T e + a_2\sum u^T u \tag{18}$$

where, e is tracking error, u is control output, α_1 and α_2 are positive constants, This study takes $\alpha_1 = \alpha_2 = 10$.

When optimizing controller parameters c, λ, h, α by genetic algorithm, first determine the range of each parameter and the length of code using binary coding. Next, initial population P(0) is composed by n individuals randomly generated and each individual is decoded into the corresponding parameter value which is used to obtain objective function J and fitness function value f. Take f =1/J, where J is given by formula (18). Then use the copy, crossover and mutation operator for population P(t) to generate the next generation population P(t + 1). Finally the steps are repeated cycle until established targets or parameter convergence is met.

SIMULATION RESEARCH

During the practical measurement of system parameters ,moment of inertia J is $0.0253 kg.m^2$, friction coefficient f is 0.01, drill pipe speed n_0 changes in the range of 60 ±6(r/min),slurry viscosity coefficient μ changes in the range of $12\pm1.2\times10^{-3}$. Let deviation angle DEV = 15° and electromagnetic torque of upper turbo-dynamotor M_U = 0.15N.m. The set output tool face angle is 60 sin(2t)°. In GA designing, crossover probability is 0.4, mutation probability is 0.2, population size is 30 and evolution generation is 20. First choose c = 60, λ = 5, h = 3, α = 6 by experience and then those parameters are optimized using genetic algorithm. The searching range and optimized value of each parameter are shown in Table 1. Simulation results are shown in Fig. 5 to 10.

Table 1: Optimization of control parameters

Control parameters	Min. value	Max. value	Optimized value
C	30	200	147.51
λ	2	15	9.7900
h	1.5	8	4.5600
α	3	20	11.260

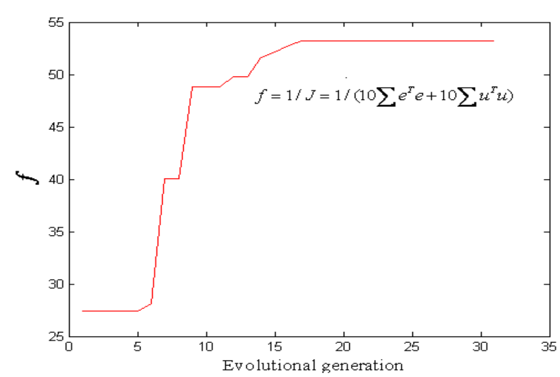

Fig. 5: Best individual fitness

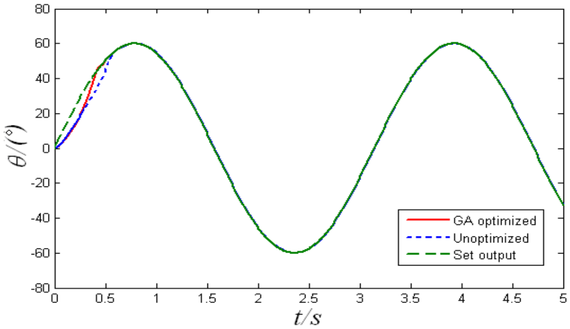

Fig. 6: Output tool face angle

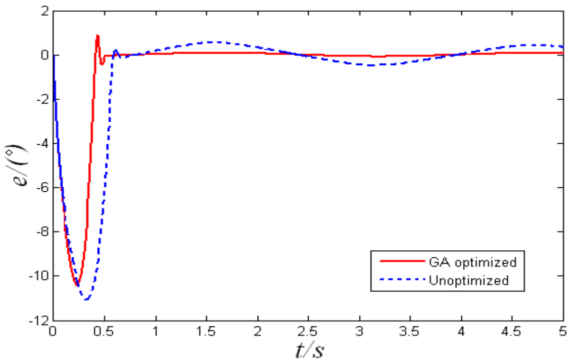

Fig. 7: Tracking error

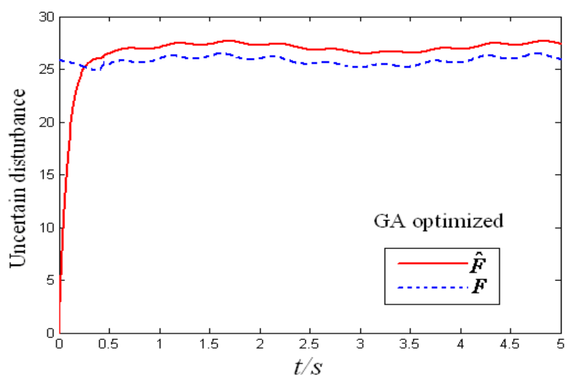

Fig. 8: Uncertain disturbance and observation value

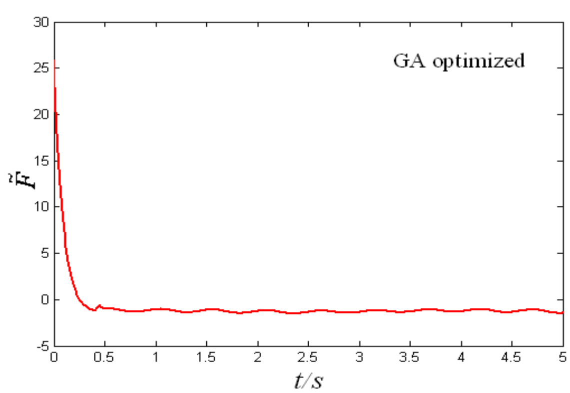

Fig. 9: Observation error

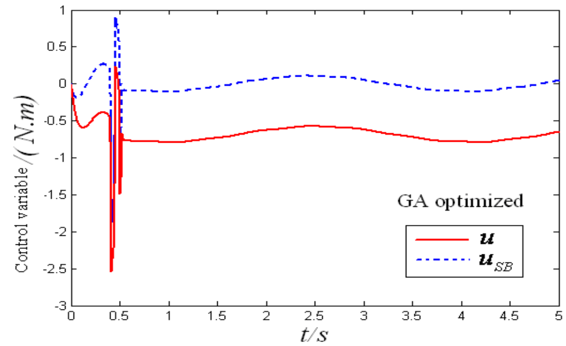

Fig. 10: Total control variable and sliding mode control variable

From the simulation results above we can see that the best individual fitness is 53.3816 and system begin to converge after 17 iterations. In such a case, the corresponding optimized sliding mode controller parameters are shown in Table 1. Obviously, NDO can observe most disturbance, the performance and robustness of sliding mode controller optimized by GA are significantly improved.

CONCLUSION

Rotary steering drilling stabilized platform is easily subjected to the influence of outside interference, drilling technology and geometrical parameter perturbation of borehole under work condition and the upper bound of uncertain disturbance is often unknown. This study proposes a novel sliding mode control strategy based on NDO and GA optimization. At first, the total uncertain disturbance is observed by NDO and then the system robustness is guaranteed using sliding mode control. Furthermore, the adaptive law of switching gain is also designed and bipolar sigmoid function is used to replace sign function to weaken chattering. Finally, the four key parameters of controller are optimized by GA to get optimal control performance and robustness. This study provides a new method for robust control of stabilized platform, thus it has some engineering and academic significance.

ACKNOWLEDGMENT

The authors would like to appreciate the support of Chongqing Educational Committee Science and Technology Research Project (KJ121407) and Chongqing University of Science and Technology Intramural Scientific Foundation (CK2011B11).

REFERENCES

Chen, P.C., P.W. Chen and W.L. Chiang, 2011. Linear matrix inequality conditions of nonlinear systems by genetic algorithm-based H∞ adaptive fuzzy sliding mode controller. J. Vib. Control, 17(2): 163-173.

Cui, Q.L., S.H. Zhang and Y.X. Liu, 2007. Study on controlling system for variable structure of stabilized platform in rotary steering drilling system. Acta Petrol. Sinica, 28(3): 120-123.

Ding, G., J. Liu and J. Zhang, 2012. Sliding mode control scheme for uncertain linear systems. Adv. Mat. Res., 562-564: 2065-2068.

Douiri, M.R., M. Cherkaoui and A. Assadki, 2012. Genetic algorithms based fuzzy speed controllers for indirect field oriented control of induction motor drive. Int. J. Circuits Syst. Signal Process., 6(1): 21-28.

Fei, J.T. and H.F. Ding, 2012. Adaptive sliding mode control of dynamic system using RBF neural network. Nonlinear Dyn., 70(2): 1563-1573.

Geoff, D., 2000. The new direction of rotary steering drilling. Oilfield Rev., 12(1): 18-29.

Huo, A.Q., L. Ge, L.Z. Yuan and H.Y. Huang, 2010a. Cascade fuzzy algorithms research of stabilized platform in rotary steering drilling system. Petrol. Instrument., 24(1): 4-6.

Huo, A.Q., Y.Y. He, Y.L. Wang, *et al*., 2010b. Study of fuzzy adaptive sliding mode control for rotary steering drilling sable platform. Comput. Simul., 27(10): 152-155.

Li, Y.D., W.B. Cheng, N. Tang, *et al*., 2010. The intelligent PID control of the rotary navigational drilling tool. China Petrol. Mach., 38(8): 13-16.

Liu, W.J., Q.M. Sui and H.R. Xiao and F.G. Zhou, 2011. Sliding backstepping control for ship course with nonlinear disturbance observer. J. Inform. Comput. Sci., 8(16): 3809-3817.

Noh, I., S.C. Won and Y.J. Jang, 2012. Non-interactive looper and strip tension control for hot finishing mill using nonlinear disturbance observer. ISIJ Int., 52(6): 1902-1100.

Rani, M.R., H. Selamat, H. Zamzuri, *et al*, 2012. Multi-objective optimization for PID controller tuning using the global ranking genetic algorithm. Int. J. Innov. Comput. I., 8(1A): 269-284.

Xue, Q.L., L.G. Han, J.Z. Yang, L.L. Huang and B.Q. Shi, 2010. Study on controlling simulation system for Stabilizing platform in rotary steering drilling system. Petrol. Drill. Tech., 38(4): 10-14.

Yeh, F.K., 2012. Attitude controller design of mini-unmanned aerial vehicles using fuzzy sliding-mode control degraded by white noise interference. IET Control Theory A., 6(9): 1205-1212.

Zhang, Y.T., T.F. Li and J. Yi, 2012. Adaptive neural network sliding mode control based on particle swarm optimization for rotary steering drilling stabilized platform. Int. J. Adv. Comput. Technol., 4(19): 107-114.

Zhao, Z.S., J. Zhang and L.K. Sun and G. Ding, 2011. Higher order sliding mode control with self-tuning law for a class of uncertain nonlinear systems. Control Dec., 26(8): 1277-1280.

Zhi, Q. and Y.L. Cai, 2012. Nonlinear disturbance observer based aerodynamic force and direct thrust blended controller design for kinetic kill vehicles. Control Dec., 27(4): 579-583.