Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

A Blended Autopilot for Dual Control Missile Using Generalized Predictive and Adaptive Terminal Sliding Mode Control

Chang Yafei* Yuan Ruyi* Fan Guoliang* Yi Jianqiang*

**Institute of Automation, Chinese Academy of Sciences, 100190, Beijing
(Tel: 86+13810688872; e-mail: yafei.chang@ia.ac.cn).*

Abstract: A blended autopilot algorithm is developed using generalized predictive control and adaptive non-singular terminal sliding mode control, for dual control missile steered by combination of aerodynamic fins and reaction jets. The blended algorithm considers the reaction jets control design prior due to its inherent control error, and then treats the aerodynamic fin control on the basis of the reaction jets control results. The generalized predictive control method is applied to the reaction jets control, which could make the missile achieve desired performance with a small number of consumed reaction jets. Then a novel adaptive non-singular terminal sliding mode control method is proposed for the aerodynamic control system design, to meet the requirements of robustness and fast response for the control of the missile. The unknown bound of the uncertainties and disturbances is estimated adaptively in the control, which makes the control with better robustness. Using the Lyapunov stability theory, the finite time convergence in both reaching and sliding phases is achieved. Finally, the simulations are conducted on the nonlinear longitudinal missile model with uncertainties and disturbances, and the simulation results demonstrate the effectiveness of the blended autopilot algorithm.

Keywords: Dual control missile, generalized predictive control, terminal sliding mode control, Lyapunov stability, robustness.

1. INTRODUCTION

Modern interception strategy requests anti-air missiles to hit to kill the target, which requires the missile control system having fast response. The traditional missiles with fins-only can hardly achieve a sufficiently fast response, since effectiveness of tail fins depends highly on the dynamic pressure especially at high attitude (Barnes and Brown, 1998). Moreover, fins-only missiles have a non-minimum phase characteristic which causes a large undershoot (Wise and Broy, 1998). To compensate this situation, alternative control technologies have to be used. Possible options are propulsion-based control in the forms of a reaction jet control system (RCS) combined with fin control, and the compensated missile is often called dual control missile (Tournes, *et al.*, 2006; Shtessel, *et al.*, 2006). There are two types of RCS configuration, the direct force type and the moment type. The RCS is located near the centre of gravity (c. g.) arising the acceleration directly in the former type, and in ahead of or in rear of c. g. arising the force and the moment in the later type (Hirokawa and Sato, 2001). The paper here concentrates on missiles of the moment type, which is based on PAC-3 configuration shown in Fig.1.

The participation of the reaction jets brings problem of its control coordination with fins. Researches in (Idan, *et al.*, 2007) adopted command allocation strategy, with which the angle command was divided into two parts: one was assigned to the aerodynamic system and the other was to the RCS. The advantage of this strategy is easy to design, but the coupling of these two systems is not considered and the entire system stability is hard to be satisfied. Control quantity allocation strategy was proposed in researches (Ridgely, *et al.*, 2006; Cui, *et al.*, 2011), which considered the aerodynamic system design and the reaction jets system design together, and assigned the desired control quantity to these two actuators. However, the reaction jets output in these researches was regarded as continuous variable. If it was regarded as discrete in accordance with reality, control error would happen as the reaction jets can hardly produce the accurate allocated control quantity. Here in this paper, the RCS is first considered due to its inherent control error caused by their discrete trait, and then the aerodynamic fin control is designed based on the reaction jets control results. This method guarantees the entire system stability and control accuracy. In addition, the researches in (Idan, *et al.*, 2007; Ridgely, *et al.*, 2006; Cui, *et al.*, 2011) didn't take consumption of reaction jets into consideration. As the reaction jets amount is limited, it is necessary to consider the control effort of the RCS. Thus generalized predictive control (GPC) method is adopted in the RCS design, since it can optimize the control effort by varying the control-weighting sequence of the cost functions during the minimization process (Geng and Geary, 1998).

The participation of the reaction jets also brings disturbances to the aerodynamic control system, which makes the missile control system feature huge nonlinearity and uncertainty. Sliding mode control (SMC) has received much attention as an efficient control technique to handle systems with large uncertainties, nonlinearities, and bounded external

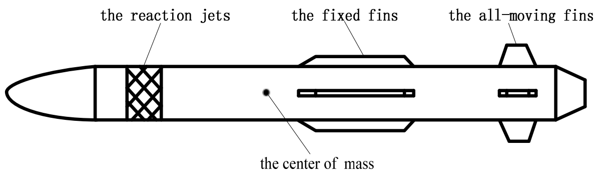

Fig. 1. Missile configuration

disturbances. The most prominent property of SMC is its insensitivity to parameter variations and external disturbances. Some aerodynamic fin control systems were designed based on SMC in (Idan, *et al.*, 2007； Tournes, *et al.*, 2006; Shtessel and Tournes, 2009). However, SMC in those researches all adopted the linear hyperplane-based sliding modes which could only achieve the asymptotic convergence in the sliding phase. In view of the requirement of fast response for the missile, terminal sliding mode control (TSMC) with finite time convergence (Feng, *et al.*, 2002; Wei, *et al.*, 2009) is a better choice. Besides, research in (Koren, *et al.*, 2008) all regarded the bound of disturbance as known in SMC design. However, the dual control missile is with unknown uncertainties in practice. In consideration of the above, a novel adaptive non-singular terminal sliding mode control (ANTSMC) method is proposed for the aerodynamic fin control system design. ANTSMC here can achieve the finite time convergence in both reaching and sliding phase and need no knowledge of the bound of the uncertainties and disturbances in advance.

In this work, a blended autopilot based on GPC and ATSMC for the dual control missile is designed to robustly improve the system time response in presence of parametric uncertainties and external disturbances. The rest of the paper is organized as follows: Section 2 describes the model of the dual control missile introduced from (Bi, 2010). Section 3 presents the blended autopilot algorithm in detail. Simulation results are demonstrated in Section 4. Finally, Section 5 provides the concluding remarks.

2. MISSILE MODEL DESCRIPTION

As the normal acceleration command from the guidance laws can be converted to the angle of attack command, we choose the angle of attack as the commanded signal. In general, the dynamic model of the dual control missile in pitch channel can be expressed in the following form (Bi, 2010)

$$\begin{cases} \dot{\alpha} = q + ((Z+F_Z)\cos\alpha - X\sin\alpha + mg\cos\mu)/mV + \Delta_\alpha \\ \dot{q} = (M_\alpha(\alpha) + M_q(q,V) + M_{\delta_e}(\alpha)\delta_e + M_f(U))/J_y + \Delta_q \end{cases} \quad (1)$$

where α is the angle of attack, μ is the angle of path, p is the pitch angular rate; m is the aircraft mass, V is the aircraft velocity; X and Z are the aerodynamic forces along the x and z body axes, F_Z is the force produced by the reaction jets; J_y is the moment of inertia along the y body axis, $M_\alpha(\alpha)$, $M_q(q,V)$, $M_{\delta_e}(\alpha)\delta_e$, and $M_f(U)$ are the static aerodynamic moment, damping moment, fin control moment, and reaction jets produced moment respectively; δ_e is the elevator deflection and U is the reaction jets fire command vector; Δ_α and Δ_q denote total uncertainties and disturbances in the missile. The aerodynamic model and the reaction jets model are not given here.

The dual control missile features huge nonlinearity and uncertainty in the dual control missile. The autopilot for such missile must be competent to handle those characteristics with strong robustness. Besides, there are two kinds of actuators with different features in the model. So, the autopilot should be able to make these two actuators corporate well. In this paper, a blended autopilot is proposed to make the angle of attack α track the angle command α_c accurately and rapidly in presence of parametric uncertainties and external disturbances.

3. BLENDED AUTOPIOLT DESIGN

As mentioned in Section 1, there always exits control errors in the RCS due to its discrete nature and limited amount. In addition, the reaction jets response much faster than the fins. Thus the RCS is designed prior; the aerodynamic fin control system is later designed on the basis of the control effort of the RCS. Further, to avoid unnecessary consumption of the reaction jets, they are not allowed to be fired under the conditions that the error between the present angle and the desired angle is small, or the calculated RCS control effort is small. Thus a firing condition is set in the blended autopilot to decide whether or not the reaction jets work. The conditions are expressed as follow:

$$\begin{cases} |e| > \dfrac{|e_0|}{k} \\ M_{fc} > M_0 \end{cases} \quad (2)$$

where $e = \alpha - \alpha_c$ is the present control error, e_0 is the initial error, M_{fc} is the calculated RCS control effort， M_0 is the threshold to M_{fc} , and k is a positive constant. Only if the condition is satisfied, which implies the error and the calculated RCS control effort are large enough, the reaction jets fire and $M_f = M_{fc}$; else $M_f = 0$. The closed-loop control system is shown in Fig.2. RCS design and the aerodynamic fin control design will be described in the following.

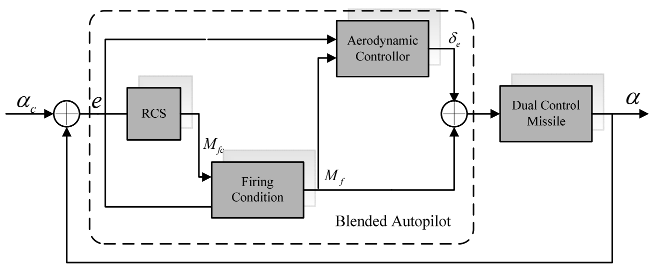

Fig. 2. The closed-loop control system structure

3.1 RCS Design

As the amount of the reaction jets is limited, the RCS should aim at improving the system response and at the same time avoiding the excessive reaction jets consumption. Thus the

RCS design should take control effort into consideration. Besides, the dual control model is with huge uncertainties. The aim of the GPC algorithm is to generate a sequence of control signals at each sampling interval which optimizes the control effort. Moreover, the GPC has low sensitivity to model error. Thus, the GPC is adopted in the RCS design.

3.1.1 GPC Algorithm

Here, a brief introduction of the GPC algorithm is given. The following CARIMA model is adopted for the plant in the GPC (Clark, *et al.*, 1987):

$$A(z^{-1})y(k) = B(z^{-1})u(k-1) + \xi(k)/(1-z^{-1}) \quad k = 0,1,2,\dots \tag{3}$$

where $A(z^{-1})$ and $B(z^{-1})$ are polynomials in the delay operator z^{-1}; $y(k)$ and $u(k)$ are output and control variables, respectively; $\xi(k)$ is an uncorrelated random sequence. Now a prediction of the plant output is given here:

$$y(k+j) = E_j\xi(k+j) + F_j\Delta u(k+j-1) + G_j y(k) \tag{4}$$

where j is the number of future time steps being predicted; E_j, F_j, and G_j result from a recursive solution of the Diophantine relation

$$\begin{cases} 1 = A(z^{-1})E_j(z^{-1}) + z^{-j}G_j(z^{-1}) \\ F_j(z^{-1}) = B(z^{-1})E_j(z^{-1}) \end{cases} \tag{5}$$

Then a predictive control law is given to minimize a cost function given by

$$J = E\{[Y - Y_r]^T[Y - Y_r] + \Delta U^T \Gamma \Delta U\} \tag{6}$$

where

$$\begin{aligned} Y &= [y(k+N_1), y(k+N_1+1), \dots, y(k+N_2)]^T \\ Y_r &= [y_r(k+N_1), y_r(k+N_1+1), \dots, y_r(k+N_2)]^T \\ \Delta U &= [\Delta u(k), \Delta u(k+1), \dots, \Delta u(k+N_u-1)]^T \\ \Gamma &= diag(\gamma_1, \gamma_2, \dots, \gamma_{N_u}) \end{aligned} \tag{7}$$

and N_1 is the minimum output horizon, N_2 is the maximum output horizon, N_u is the maximum control horizon, $y_r(k+N_1), y_r(k+N_1+1), \dots, y_r(k+N_2)$ are the desired values of the output sequence from the $(k+N_1)$ th sampling instant to the $(k+N_2)$ th sampling instant, $\gamma_1, \gamma_2, \dots, \gamma_{N_u}$ is the control-weight sequence.

According to $\partial J/\partial \Delta U = 0$, the predicted control vector can be derived as

$$\Delta U(k) = (F_1^T F_1 + \Gamma)^{-1} R_1^T [Y_r - F_2 \Delta U(k\text{-}j) - GY(k)] \tag{8}$$

where F_1, F_2, and G are matrixes derived from (4), which are not given here in detail, and one can refer to (Clark, et al., 1987).

However, only the first element of the vector is used. Then the current control is gotten as

$$\begin{aligned} u(k) &= u(k-1) + \Delta u(k) \\ &= u(k-1) + [1,0,\dots,0](F_1^T F_1 + \Gamma)^{-1} F_1^T [Y_r - F_2\Delta U(k\text{-}j) - GY(k)] \end{aligned} \tag{9}$$

3.1.2 GPC Based RCS Design

In this part, the RCS based on the GPC is developed. Assuming the missile CARIMA model is as follow

$$\begin{aligned} \alpha(k) &= (1 - A_M(z^{-1}))\alpha(k) + B_M(z^{-1})M_f(k-1) + \xi(k) \\ &= \varphi^T(k)\theta + \xi(k) \\ \varphi(k) &= [-\alpha(k-1), \dots, -\alpha(k-n_a), M_f(k-1), \dots, M_f(k-n_b-1)] \\ \theta &= [a_1, \dots, a_{n_a}, b_0, \dots, b_{n_b}] \end{aligned} \tag{10}$$

where M_f is regarded as control variable, α is regarded as the output. As the parameter vector θ is unknown, the least squares identification method is used to estimate them, which is expressed as follow:

$$\begin{cases} \hat\theta(k) = \hat\theta(k-1) + K(k)[\alpha(k) - \varphi^T(k)\hat\theta(k-1)] \\ K(k) = \dfrac{P(k-1)\varphi(k)}{\lambda + \varphi^T(k)P(k-1)\varphi(k)} \\ P(k) = \dfrac{1}{\lambda}[I - K(k)\varphi^T(k)]P(k-1) \end{cases} \tag{11}$$

where λ is the forgetting factor parameter.

Then the costing function is chosen based on the control effort and control accuracy as

$$J = E\{\sum_{j=N_1}^{N_2}[\alpha(k+j) - \alpha_c(k+j)]^2 + \sum_{j=1}^{N_2}[r_j(e_j)M_f(k+j-1)]^2\} \tag{12}$$

where $r_j(e_j) = \varepsilon_j e^{-e_j^2/c^2}$, $e_j = \alpha(k+j) - \alpha_c(k+j)$, ε_j and c are positive constants. Notably, the control-weight of the control effort is small when the current control error e_j is big, aiming at improving the angle response speed; and it is big to avoid the unnecessary consumption of the reaction jets when the error is small.

Now, the main steps of the RCS based on the GPC are as follows:

1) Initialize the control algorithm such as the order of the missile CARMA model n_a, n_b, initial value $\hat\theta(0)$, $P(0)$, control parameter N_1, N_2, N_u and forgetting factor λ.

2) Record the present angle of the attack $\alpha(k)$ and the desired $\alpha_c(k+j)$.

3) Estimate the missile CARMA model parameter $\hat\theta$, i.e. $\hat A$ and $\hat B$, using the least squares identification method (11) online.

4) Solve Diophantine equation (5) to get polynomial E_j, G_j, and F_j.

5) Build vector Y_r, $\Delta U(k-j)$, and $Y(k)$, and matrix G, F_1, and F_2.

6) Calculate $u(k)$ according to (9).

7) Let $k \to k+1$ and go to Step 2.

3.2 Aerodynamic Fin Control Design

In this section, the ANTSMC method is proposed to cope with the huge uncertainties and disturbances in the aerodynamic system, and to make the system response fast. The finite time convergence in both reaching and sliding phases is demonstrated by using the Lyapunov stability theory.

Denote the state vector $x=[x_1,x_2]^T$, and control input u as $x_1=\alpha-\alpha_c$, $x_2=q$, and $u=\delta_e$. Then the model of the aerodynamic system can be obtained as

$$\begin{cases}\dot{x}_1 = x_2+\hat{f}(x)\\ \dot{x}_2 = h(x)+g(x)u+d(x)\end{cases} \tag{13}$$

where

$$\begin{cases}\hat{f}(x)=((Z+F_Z)\cos\alpha - X\sin\alpha + mg\cos\mu)/mV - \dot{\alpha}_c + \Delta_\alpha\\ h(x)=(M_\alpha(\alpha)+M_q(q,V)+M_f(U))/J_y\\ g(x)=M_{\delta_e}(\alpha)/J_y\\ d(x)=\Delta_q\end{cases}$$

Similar with (Feng, *et al.*, 2002), the sliding surface is chosen as

$$s=x_1+(x_2+\hat{f}(x))^{p/q}/\beta \tag{14}$$

where $\beta>0$ is a design constant, and p and q are positive odd integers, which satisfy $1<p/q<2$.

Remark 1: There exits unknown term Δ_α in $\hat{f}(x)$, thus the following observer (15) is used to estimate $\hat{f}(x)$ and the observer output z_1 is used to replace it.

Consider the observer:

$$\begin{cases}\dot{z}_0=v_0+x_2, \quad v_0=-2L^{1/3}|z_0-x_1|^{2/3}sign(z_0-x_1)+z_1\\ \dot{z}_1=v_1, \quad v_1=-1.5L^{1/2}|z_1-v_0|^{1/2}sign(z_1-v_0)+z_2\\ \dot{z}_2=-1.1Lsign(z_2-v_1)\end{cases} \tag{15}$$

where $L>0$. Then z_1 converges to $\hat{f}(x)$, and z_2 converges to $\dot{\hat{f}}(x)$ in a finite time, if the state x_1 and x_2 are measured without noise (Shtessel, et al., 2007).

Assuming $d(x)$ in (13) satisfies $|d(x)|\le d_{\max}$, with $d_{\max}$ a constant but unknown, then we propose the following control law for the system (13):

$$u=-g(x)^{-1}(h(x)+\dot{\hat{f}}(x)+\beta\frac{q}{p}(x_2+\hat{f}(x))^{2-p/q}+\hat{d}_{\max}\delta\frac{s}{|s|}+\eta_1 s+\eta_2\,\mathrm{sgn}(s)) \tag{16}$$

where $\delta\ge 2$, $\eta_1,\eta_2>0$, and $\hat{d}_{\max}$ is an estimation of unknown scalar $d_{\max}$, which is determined by the following updating law:

$$\dot{\hat{d}}_{\max}=\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}\delta|s| \quad (\hat{d}_{\max}(0)>0) \tag{17}$$

Remark 2: $\hat{f}(x)$ in (16) is also replaced by the observer output z_1. In addition, as the analytical expression of $\dot{\hat{f}}(x)$ in (16) cannot be derived, thus it is replaced by the observer output z_2.

Then we have the following result.

Theorem 1: Consider the system (13) with the non-singular terminal sliding surface (14). Then using the control law (16) and the updating law (17), the state of the system can reach the sliding surface in finite time and then convergence to the origin along the sliding surface in finite time too.

Proof: In the reaching phase ($s\ne 0$), taking the time derivative of (14) along (13) renders to

$$\dot{s}=x_2+\hat{f}(x)+\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(h(x)+g(x)u+d(x)+\dot{\hat{f}}(x)) \tag{18}$$

Substituting (16) in to (18) yields

$$\dot{s}=\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(d(x)-\hat{d}_{\max}\delta\frac{s}{|s|}-\eta_1 s-\eta_2\,\mathrm{sgn}(s)) \tag{19}$$

Let $\tilde{d}_{\max}=d_{\max}-\hat{d}_{\max}$. Consider the following Lyapunov function candidate:

$$V_1=\frac{1}{2}s^2+\frac{1}{2}\tilde{d}_{\max}^2 \tag{20}$$

Differentiating (20) with respect to time and using (19) and (17) render to

$$\begin{aligned}\dot{V}_1 &= s\dot{s}+\tilde{d}_{\max}\dot{\tilde{d}}_{\max}\\ &=\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(d(x)s-\hat{d}_{\max}\delta|s|-\eta_1 s^2-\eta_2|s|-\tilde{d}_{\max}\delta|s|)\end{aligned} \tag{21}$$

Since p and q are positive odd integers and $1<p/q<2$, there is $(x_2+\hat{f}(x))^{p/q-1}\ge 0$. Then it becomes

$$\begin{aligned}\dot{V}_1 &\le \frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(d_{\max}|s|-d_{\max}\delta|s|-\eta_1 s^2-\eta_2|s|)\\ &=\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(d_{\max}|s|(1-\delta)-\eta_1 s^2-\eta_2|s|)\\ &\le -\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}\eta_2|s|\le 0\end{aligned} \tag{22}$$

which implies that $V_1(t)=\frac{1}{2}s^2+\frac{1}{2}\tilde{d}_{\max}^2\le V_1(0)$. Hence, s and $\tilde{d}_{\max}$ are bounded.

Furthermore, consider another Lyapunov function candidate

$$V_2=\frac{1}{2}s^2 \tag{23}$$

Differentiating (23) with respect to time and using (19) we obtain

$$\begin{aligned}\dot{V}_2 &= s\dot{s}\\ &\le \frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}((d_{\max}-\hat{d}_{\max}\delta)|s|-\eta_1 s^2-\eta_2|s|)\end{aligned} \tag{24}$$

From $\hat{d}_{\max}>0$ and $\dot{\hat{d}}_{\max}=\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}\delta|s|\ge 0$, we can obtain $\hat{d}_{\max}(t)\ge\hat{d}_{\max}(0)>0$.

Choosing $\hat{d}_{\max}(0)$ large enough, one can obtain that

$$\begin{aligned}d_{\max}-\hat{d}_{\max}(t)\delta &\le d_{\max}-\hat{d}_{\max}(0)-\hat{d}_{\max}(0)\\ &=\tilde{d}_{\max}(0)-\hat{d}_{\max}(0)\le 0\end{aligned} \tag{25}$$

Substituting (25) in to (24) yields

$$\begin{aligned}\dot{V}_2 &= s\dot{s}\\ &\le \frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}(-\eta_1 s^2-\eta_2|s|)\\ &\le -\frac{p}{q\beta}(x_2+\hat{f}(x))^{p/q-1}\eta_2|s|\end{aligned} \tag{26}$$

Then, the sliding mode $s=0$ can be reached from anywhere in the phase plane in the finite time according to the analysis in (Feng, et al., 2002).

In the sliding phase (s=0)

$$\dot{x}_1=-\beta x_1^{q/p} \tag{27}$$

Consider $V_3 = \frac{1}{2}x_1^2$ as a candidate Lyapunov function of (27). By differentiating V_3 with respect to time and substituting (27) into it, we have

$$\dot{V}_3 = x_1\dot{x}_1 = -\beta x_1^{q/p+1} = -\beta 2^{(p+q)/2p} V_3^{(p+q)/2p} \quad (28)$$

According to (Wei, et al., 2009), the system states converge to the origin along the sliding surface in finite time. This completes the proof.

Remark 3: It should be noted that the ANTSM control (16) is always non-singular in the state since $1 < p/q < 2$.

Remark 4: $\eta_1 s$ in (16) is exponential approach item, which is designed to make the system possess a fast approach speed when the sliding surface is big. $\hat{d}_{\max}$ in (16) is designed to estimate the uncertainties bound in the model, which makes the choice of the control parameter independent on the uncertainties. Besides, the adaptive $\hat{d}_{\max}$ helps improve the system robustness.

Remark 5: In order to eliminate chattering, a saturation function *sat* can be used to replace the sign function *sgn*.

4. SIMULATION RESULTS

In this section, the performance of the proposed blended autopilot algorithm is evaluated for the dual control missile as shown in (Bi, 2010). The control objective is to make the angle of attack α track the angle command α_c rapidly and accurately in the presence of disturbances and uncertainties. First, the control parameter is given. Then, we present a comparison between the dual control missile and fin-only control missile in which the RCS doesn't work. Next, the proposed ANTSMC method is compared with the traditional SMC applied to the dual control missile in this paper. The robustness of the proposed blended autopilot algorithm is then discussed.

1.1 Simulation Parameters

The angle command is set as $\alpha_c = 10^\circ$ at 0.1 sec after the simulation starts, and the simulation begins from the trimmed equilibrium state $\delta_e = -0.70^\circ$, $\alpha = 1.15^\circ$, and $V_t = 1000m/s$. The control parameters in the RCS are given here: the order of identification model $n_a = 5$, $n_b = 3$, the minimum and maximum output horizon $N_1 = 1$, $N_2 = 4$, the maximum control horizon $N_u = 4$. The control parameters in the aerodynamic control system are given here: $\beta = 4$, p=15, $q = 13$, $\eta_1 = 5$, $\eta_2 = 3.5$.

1.2 Comparison Between the Dual Control Missile and Fin-only Control Missile

The reaction jets improve the system response speed only when the coordination method and the RCS control method are designed effectively. To verify the effectiveness of the proposed blended autopilot, the dual control missile is compared with the fin-only control missile. The control parameters of the aerodynamic control system are all same.

The simulation comparison curves of the angle of attack are shown in Fig. 3. We can observe the dual control missile is with much faster response speed than the fin-only control missile, which shows the effectiveness of the proposed coordination method and the RCS control method. Fig. 4 shows the output of the reaction jets, from which we are informed the reaction jets work at the beginning of the response and stop while the angle achieves the desired command. This shows the unnecessary fire doesn't happen.

1.3 Effectiveness of the Proposed ANTSMC Method

To verify the effectiveness of the proposed ANTSMC method, it is compared with the traditional SMC with linear sliding surface and without the adaptive term. The other control parameters are all same in those two methods.

Fig. 5 shows the comparison curves of the angle, from which we can observe the dual control missile with the proposed ANTSMC method has a faster convergence speed.

1.4 Robustness Verification of the Dual Control Missile System with the Blended Autopilot

To certify the robustness of the blended autopilot, uncertainties $\Delta_\alpha = 0.5Z$ and $\Delta_q = 0.5M_q(q,V)$ are added to the dual control missile. The comparison curves between the angle response with and without uncertainties is shown in Fig. 6, from which we can obtain the system possesses good robustness.

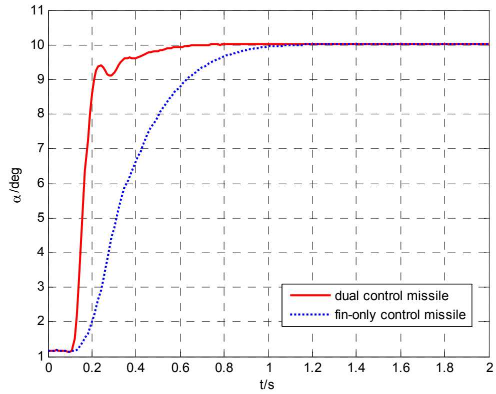

Fig. 3. Comparison of α with the dual and fin-only control

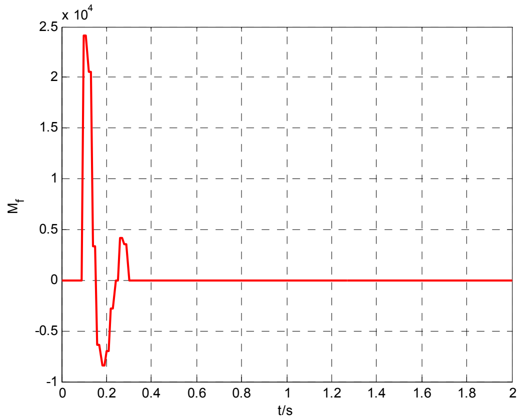

Fig. 4. Control output of the RCS

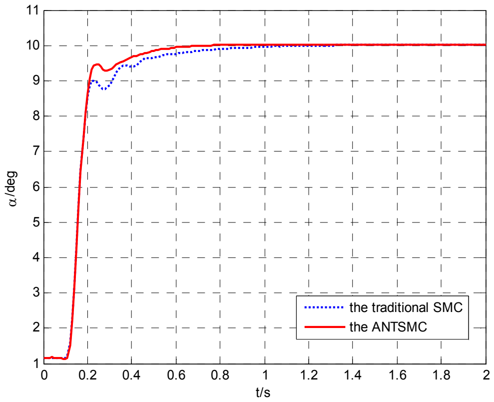

Fig. 5. Comparison of α with the ANTSMC and SMC

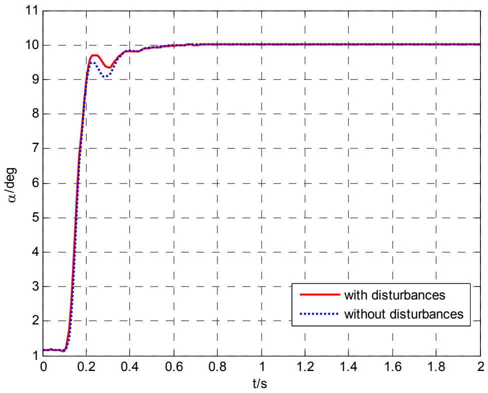

Fig. 6 Comparison of α with and without disturbances

5. CONCLUSION

This paper presents a new blended autopilot algorithm for missile steered by combination of aerodynamic fins and reaction jets. To improve the system response speed and at the same time avoid the excessive reaction jets consumption, the generalized predictive control is adopted in the RCS design. Then an adaptive non-singular terminal sliding mode control is proposed to cope with the huge uncertainties and disturbances in the aerodynamic control system, and to improve the state convergence speed. The finite time convergence in both reaching and sliding phase is guaranteed and demonstrated by using the Lyapunov stability theory. Finally, the fast response performance and robustness of the dual control missile with the proposed blended autopilot are demonstrated through simulations.

ACKNOWLEDGMENT

This work was partly supported by the National Natural Science Foundation of China (Grants No. 61203003, 61273149, 61273336) and the Special Project for Innovation Methods of MOST (Grant No.2012IM010200).

REFERENCES

Barnes, R.S. and K.N. Brown (1998). Patriot Advanced Capability-Three (PAC-3) - The First Deployable Hit-to-Kill Technology. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-19881127-015, Monterey.

Bi, Y.T. (2010). Research on Guidance and Control for Missile with Lateral Jets and Aerodynamic Surfaces. Ph.D. Dissertation of Harbin Institute of Technology.

Cui, L. and Y. Yang (2011). Disturbance Rejection and Robust Least-Squares Control Allocation in Flight Control System. *Journal of Guidance, Control, and Dynamics*, 34 (6), 1632-1634.

Clarke, D.W., C. Mohtadi and P. S. Tuffs (1987). Generalized predictive control, Part Ⅰ and Ⅱ. *Automatica*, 23 (2), 137-160.

Feng, Y., X. H. Yu and Z. H. Man (2002). Non-singular Terminal Sliding Mode Control of Rigid Manipulators. *Automatic*, 38 (2), 2159-2167

Geng, G. and G. M. Geary (1998). The Control of Input-Constrained Nonlinear Processes Using Numerical Generalized Predictive Control Method. *IEEE Transactions on Industrial Electronics*, 45(3), 496-501.

Hirokawa, R. and K. Sato (2001). Autopilot Design for a Missile with Reaction-Jet Using Coefficient Diagram Method. In *the Proceeding of AIAA Guidance, Navigation, and Control Conference and Exhibit*, Montreal, Canada, AIAA-2001-4162.

Idan, M., T. Shima and O. M. Golan (2007). Integrated Sliding Mode Autopilot-Guidance for Dual-Control Missiles. *Journal of Guidance, Control, and Dynamics*, 30(4), 1081-1089.

Koren, A., M. Idan and O. M. Golan (2008). Integrated Sliding Mode Guidance and Control for a Missile with On-Off Actuators. *Journal of Guidance, Control, and Dynamics*, 31(1), 204-214.

Ridgely, D. B., Y. Lee and T. Fanciullo (2006). Dual Aero/Propulsive Missile Control - Optimal Control and Control Allocation. In *the Proceeding of AIAA Guidance, Navigation, and Control Conference and Exhibit*, Keystone, Colorado, AIAA-2006-6570.

Shtessel, Y., C. H. Tournes and I. Shkolnikov (2006). Guidance and Autopilot for Missiles Steered by Aerodynamic Lift and Divert Thrusters using Second Order Sliding Modes. In *the Proceeding of AIAA Guidance, Navigation, and Control Conference and Exhibit*, Keystone, Colorado, AIAA-2006-6784.

Shtessel, Y. and C. H. Tournes (2009). Integrated Higher-Order Sliding Mode Guidance and Autopilot for Dual-Control Missiles. *Journal of Guidance, Control, and Dynamics*, 32(1), 79-94.

Shtessel, Y., I. A. Shkolnikov and A. Levant (2009). Guidance and Control of Missile Interceptor using Second-Order Sliding Modes. *IEEE Transactions on Aerospace and Electronic Systems*, 45(1), 110-124.

Tournes, C., Y. Shtessel and I. Shkolnikov (2006). Missile Controlled by Lift and Divert Thrusters Using Nonlinear Dynamic Sliding Manifolds. *Journal of Guidance, Control, and Dynamics*, 29(3), 617-625.

Wise, K. A. and D. I. Broy (1998). Agile missile dynamics and control. *Journal of Guidance, Control, and Dynamics*, 21(3), 441-449.

Wei, X. J. and G. Lei (2009). Composite Disturbance-Observer-Based Control and Terminal Sliding Mode Control for Non-Linear Systems with Disturbances. *International Journal of Control* , 82(6), 1082-1098.