

A Novel BTT and STT Switch Control for Surface-to-Air Missiles

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Abstract—To solve the problems that bank-to-turn (BTT) control is highly coupled and do not have a fast response time as well as that skid-to-turn (STT) control lacks of flying stability, this paper divides flight time of surface-to-air missile (SAM) into two stages by fully taking the advantages of both BTT and STT control. In this paper, Coordinated BTT controller and STT controller are designed to control angle of attack, sideslip angle and rolling angle. Based on the distance between target and missile, the switch control logics changes from coordinated BTT control to STT control to ensure the stability, response time and mobility of flight. The simulation in the paper proves the validity and stability of this method.

Keywords—Coordinated BTT; STT; switch control

I. INTRODUCTION

In order for surface-to-air missile (SAM) to attack the movable targets, SAM must be highly mobile and flexible [1]. The traditional method applied to SAM is the Skid-to-turn (STT) control, which is not stable during the fly. With the development of new spacecraft, high stability and mobility has been putting forward, and also, as the development of new aerodynamic layout, bank-to-turn (BTT) came into reality. However, BTT control also has deficiencies, which is cross-coupled and not flexible. Hence the missile needs to frequently change its maximum left surface while approaching the target. It may cause the time delay issue and will be hard for system to control. Therefore, the combination of STT and BTT is a good way to take advantage of merits and overcome the each deficiencies.

James R. Cloutier and his colleagues puts forward a nonlinear SDRE in [2], considering the velocity and accelerated velocity effect. In paper [3], Pang Rui puts forward another Hybrid BTT/STT controller to make up for the deficiency in [2], which designs its BTT/STT logics depending only on overload. Considering the complexity in tracking the target in the air, and the logics changing based on overload, the system may frequently change its logics and cause time uncertainty and control difficulty. In this paper, considering the advantages and disadvantages from pure BTT control and pure STT control, also considering to improve the coordination of missile's turning process based on movement coupled.

Take the SAM as example, this research separated the whole flying process into two phases, using coordinated BTT control has main control method to ensure the stability and high climbing mobility in the first phase, and using the STT control to ensure the flexibility and low latency in the second phase

while approaching the target. The switching condition based on the distance between target and missile to ensure the stability of the whole system and not being frequently changes based on the overload of the missile.

The remainder of this paper is arranged as follows: in the section II, mainly build up and introduce the missile system model and the BTT/STT switching logics as well as BTT/STT hybrid controller design; in the section III, mainly establish the simulation for BTT/STT controller performance and simulation of process of tracking a movable target; in the section IV, mainly make a conclusion about our BTT/STT switch control method.

II. BTT/STT SWITCH CONTROL DESIGN

A. Notations

The notations in this paper is shown in table I.

TABLE I. NOTATIONS AND EXPLANATION

Notations	Explanation
x, y, z	x, y, z position of missile in the world-frame
$\dot{x}, \dot{y}, \dot{z}$	velocity of missile in the world-frame
α	angle of attack
β	angle of sideslip
θ	angle of tilt
γ_c, ψ_c	dead reckoning dip angle and drift angle
ϑ, ψ, γ	Euler pitch, yaw, and roll angles
N_y, N_z	normal overload and lateral overload
$\delta_x, \delta_y, \delta_z$	aileron, elevator, and rudder fin deflections
M_x, M_y, M_z	moment about body-frame x, y, z -axes
F_x, F_y, F_z	force about body-frame x, y, z -axes
$\omega_x, \omega_y, \omega_z$	angular velocity about body-frame x, y, z -axes

B. System Dynamics

The system of the surface-to-air missile with the aerodynamics and kinematics is described in figure 1.

For the missile dynamics block, the input signals are the rudder partial order $\delta_x, \delta_y, \delta_z$ from the rudder. The output signals are α, β, γ_c and $\omega_x, \omega_y, \omega_z$. According to the missile dynamics, the angle of attack, angle of sideslip, and angle of rolling around velocity x are:

$$\begin{cases} \alpha = \arcsin\left(\frac{\cos\theta(\sin\theta\cos\gamma\cos(\psi-\psi_c)-\sin\gamma\sin(\psi-\psi_c))-\sin\theta\cos\theta\cos\gamma}{\cos\beta}\right) \\ \beta = \arcsin(\cos\theta(\cos\gamma\sin(\psi-\psi_c)+\sin\theta\sin\gamma\cos(\psi-\psi_c))-\sin\theta\cos\theta\sin\gamma) \\ \gamma_c = \arcsin\left(\frac{\cos\alpha\cos\beta\sin\theta-\sin\alpha\sin\beta\cos\theta+\cos\beta\sin\gamma\cos\theta}{\cos\beta}\right) \end{cases} \quad (1)$$

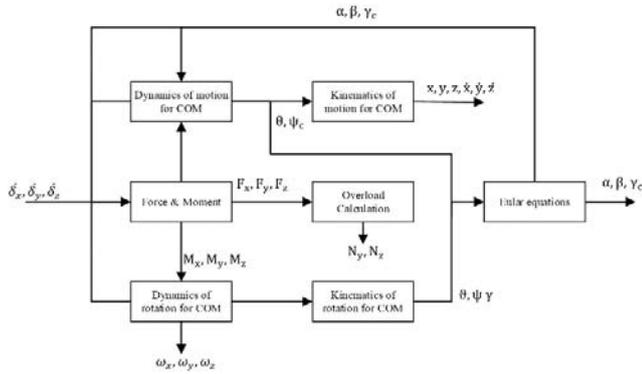


FIGURE I. MISSILE DYNAMICS

C. The BTT/STT Control Logics Design

Take the SAM as an example, we can separate the flying status into two periods. In the first period, BTT controller takes the control, and in the second period as the missile approaching the target, STT controller takes the control.

Assuming that the distance between missile and target is d_{tm} . Setting a logics switch distance \tilde{d}_{tm} , where \tilde{d}_{tm} can be measured by satellites or optical tracking instrument.

1) *BTT control law when $0 \leq d_{tm} \leq \tilde{d}_{tm}$* : If $d_{tm} \leq \tilde{d}_{tm}$, BTT controller will be applied, and the couple situation will be considered.

BTT control is a classical three channels control. Especially in the turning process, motion couple phenomenon will be obvious. According to the motion analysis in [3], there is an equiphase relationship between sideslip overload and lateral overload. Controlling the lateral overload N_z can be equally regarded as controlling the angle of sideslip β .

Hence, the coordinated BTT control algorithm can be described as follows.

$$\begin{cases} \delta_x = K_{pg}(\gamma_c - \gamma) - K_{dg}\omega_x \\ \delta_y = -K_{pp} \int (n_{zc} - n_z)d - K_{dp}\omega_y + K_x(\omega_x + \tan \alpha + \omega_y) \\ \delta_z = K_{pf} \int (n_{yc} - n_y)d - K_{df}\omega_z \end{cases} \quad (2)$$

In the ruder angle coordinated loop, the rudder angle δ_y can be depress by the integral circuit K_{pp} and couple with the angle of attack α and rolling angle ω_x .

2) *STT control law when $\tilde{d}_{tm} \leq d_{tm} < d_{tm}$* : $\tilde{d}_{tm} \leq d_{tm}$, means that missile is close to the target. Hence, STT controller is deployed. The three channels can be decoupled in this case.

In the STT controller, the rolling order is not be considered in the controller, the STT control algorithm can be described as following equations:

$$\begin{cases} \delta_x = -\gamma K_{pg} - K_{dg}\omega_x \\ \delta_y = K_{pp} \int (n_{zc} - n_z)d - K_{dp}\omega_y \\ \delta_z = K_{pf} \int (n_{yc} - n_y)d - K_{df}\omega_z \end{cases} \quad (3)$$

Based on the equations (3), the control switching logics can be established:

(a) According to the difference between rudder angle δ_x and δ_y , when $d_{tm} = \tilde{d}_{tm}$, maintain the rudder angle δ_z .

(b) For rudder angle δ_x , stop exporting the rolling order γ_c from guidance law system, and correct the $\gamma \rightarrow 0$.

(c) For rudder angle δ_y , decouple the ruder angle coordinated loop, the simplest way of doing this is to disable control gain $K_x = 0$.

III. SIMULATION EXPERIENCE

The missile model for the simulation is plane symmetry distribution. All the aerodynamic parameters in the dynamics and kinematics equations are adopted from [4].

A. Simulation 1

The comparison between coordinated BTT controller and STT controller is made to show the difference between the coordinated BTT and STT controller. For the Coordinated BTT control algorithm, the controller parameters are based on PID control law and are tuned in simulation. Controller parameters are given as follows:

$$K_{pg} = 1.31, K_{dg} = 0.1, K_{pp} = 0.603, K_{dp} = 0.935,$$

$$K_x = 0.05, K_{pf} = 0.0942, K_{df} = 1.23$$

In the STT control algorithm, the following control parameters are employed:

$$K_{pg} = 1.11, K_{dg} = 0.8, K_{pp} = 0.53, K_{dp} = 0.76,$$

$$K_{df} = 2.31, K_{pf} = 0.105$$

For coordinated BTT controller, by considering its motion state, the rolling angle γ rotate to 90° , at the same time, the missile proceeds 6g normal overload. Otherwise, the STT controller proceeds the 3g normal overload and 2g lateral overload, under the STT controller, no rolling angle rotation. The result are shown in figure 2-4.

Figure 2 shows that missile proceeds 6 g normal overload N_y and 0 g lateral overload N_z under the BTT control. Figure 3 shows that missile proceeds 90° rolling angle turning under BTT control. Figure 4 shows that missile proceeds 3 g normal overload N_y and 2 g lateral overload N_z under the STT control.

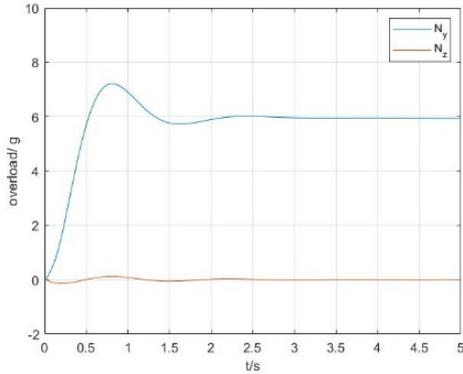


FIGURE II. OVERLOAD N_y AND N_z UNDER BTT CONTROL

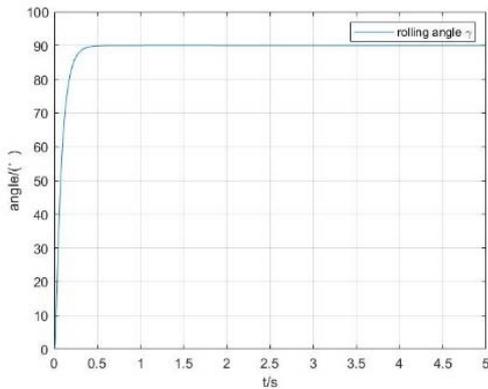


FIGURE III. ROLLING ANGLE Γ UNDER BTT CONTROL

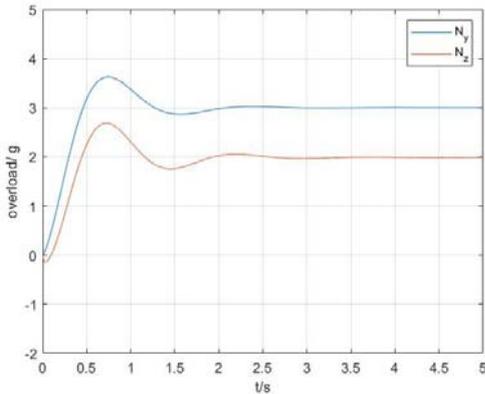


FIGURE IV. OVERLOAD N_y AND N_z UNDER STT CONTROL

This simulation indicates that the coordinated BTT control can provide enough big overload at the maximum left surface of the missile and STT control can provide satisfied mobility—y-axis and z-axis overloads. This simulation also verifies that control parameters are reasonable to meet the control requirements.

B. Simulation 2

The BTT and STT switch control performance will be discussed when tracking the target in the sky. Since this controller is applied to SAM, the following assumptions are made:

- (1) Position change of mass center is ignored while the fuel consumption.
- (2) The earth rotation and gravitational acceleration vector are assumed to be constant.
- (3) The static wind changes is ignored.

Simulation description: the target altitude is $Y_t = 2000m$, the missile altitude is $Y_m = 0m$, the distance between target and missile is $X_t - X_m = 10000m$, the target cross range $z_t = 200m$, the initial missile velocity $V_0 = 2.05Ma$, the target deviates from the missile and do a sinusoidal escape after 3000m, the escape velocity of target $V_t = 0.88Ma$.

The missile guidance law is proportion guidance. The time constant $T_g = 0.1s$, the guidance ration $K_g = 6$. The simulation results are shown in figure 5-8.

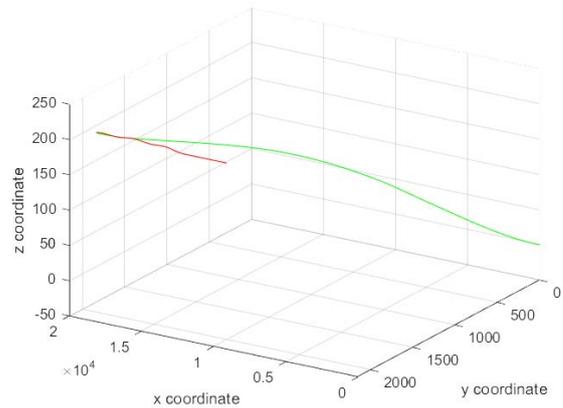


FIGURE V. 3D TRACKING MAP

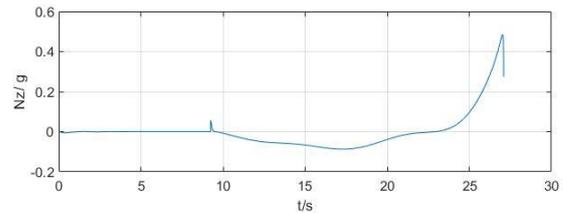
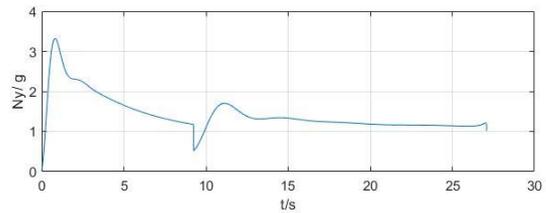


FIGURE VI. OVERLOAD N_y AND N_z

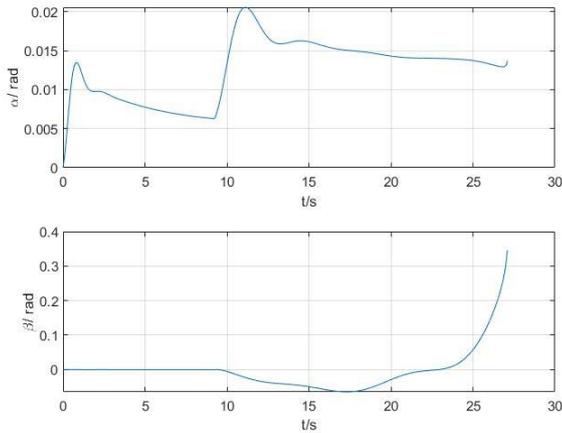


FIGURE VII. ANGLE OF ATTACK α AND ANGLE OF SIDESLIP β

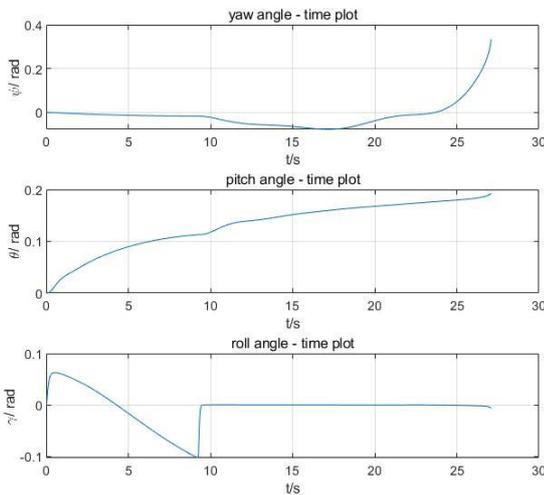


FIGURE VIII. ROLL, PITCH AND YAW ANGLE OF MISSILE STATE

According to the figure 7, in the coordinated BTT Control, the control wing and engine could provide enough y-axis overload. By changing the maximum left surface, it allows the missile climb quickly to a certain altitude. Under the control of coordinated BTT controller, the angle of sideslip β can be perfectly controlled at around zero degree during the first stage of tracking the target, which makes the missile more stable.

Stage 2, when the STT works, turning maneuver can be provided by the overload n_z in z direction. It relies on the angle of sideslip β . In the last period, the target is doing a sinusoidal maneuver to escape, STT still maneuvers the missile by changing the angle of attack α .

IV. CONCLUSION

This paper, take SAM as an example, based on the flying distance between target and missile, separating the flying process of missile into two stages. In the first stage, to ensure the flying and climbing stability, BTT control will be applied and

give the command signals. In the second stage when missile is closed to the target, STT control will be deployed to guarantee mobility of hitting the target based on distance switch logics.

According to the nonlinear missile dynamics model with symmetrical surface, this paper gives out the design method of the coordinated coupled three channels BTT controller, the decoupled pitch-roll-yaw channels STT controller, and the distance logics switch proportional boot module. Through the target tracking simulated experiment, verifying that the validity and stability of this method. Indicating that by taking the advantages of both BTT and STT control, this method can not only ensure the flying stability of earlier stage, but also promise the mobility when approach the target.

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