

# A Multiple Projectiles Weapon System Scheme and Hardware In-the-loop Simulation for Air-defense Rolling Missiles

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**Abstract.** In order to deal with future systematized, networking and intelligent warfare, the overall technology of a multiple projectiles weapon system for air-defense rolling missiles is studied. The system guidance model, the missile model and the stability control model are introduced. The three point guidance law and dual channel control equation of state in quasi-body coordinate system for rolling missile are emphatically analyzed, and the reliability and stability of the system are verified by constructing a Hardware In-the-Loop Simulation experiment joined with rolling gyro and damping gyro. The simulation result shows that the system has good stability and consistency with different conditions of interference and radar modes. The pitch-yaw channels are decoupled. There are no lost frames and false frames in the simulation cycle.

## 1 Introduction

Rolling missiles are a typical air-defense missiles. They are characterized by the stable rotation of missiles around their longitudinal axes. They have symmetrical aerodynamic layouts, which makes the pitch channel control model and yaw channel's have similarities. The control model of rolling missiles is simple and facilitate engineering implementation[1]. But with the development of modern missile defense technology and radar jamming technology, it is more difficult for a rolling missile to hit a target independently. In order to adapt to systematized, networked and intelligent future war, multiple projectile of rolling missiles can be used to break through missile defense system of enemy and increase target hit rate.

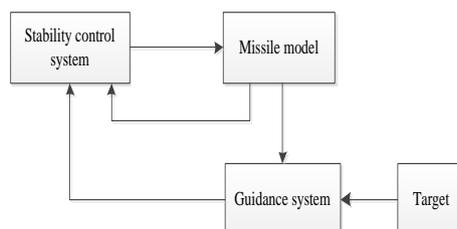
To effectively deal with the radar jamming of the enemy, the radars of the guidance station can use the photoelectric tracking radar or the phased array radar in this multiple projectiles weapon system scheme. The transmitter can choose the appropriate radar mode according to the actual situation of the battlefield, or choose double-radar modes. The radar modes are combined and the missiles coordinate with each other in flight to improve anti radar jamming capability. At present, this weapon system scheme has begun to carry out engineering practice. This paper mainly analyzes the guidance control system of this multi-strikes rolling missiles, where rolling gyros and damping gyros are added to build a Hardware In-the-Loop simulation(HILS).The simulation results are stable and reliable, and the pitch-yaw channels are decoupled, which verify the correctness and stability of the scheme.

## 2 Guidance control system

The control principle of rolling missile can be simplified into three parts of Fig. 1: the guidance system, the missile model and the stability control system. The guidance system is used to search, discover, track and guide the missile to hit the target in accordance with the predetermined guidance law. The



missile model includes the dynamic model and the kinematics model of the missile which adopt the ‘instantaneous balance’ hypothesis[2].The missile model studies the ballistic problem. It is the controlled object of the stability control system. The stability control is used to stabilize the flight attitude of the missile, and control the missile to maintain the predetermined flight state under various interference actions and change the missile flight status in time response to the order of the steering mechanism. The following is a brief analysis of the three subsystems of rolling missile.



**Figure 1.** Simplified control principle

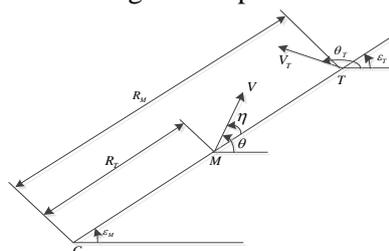
*2.1 The guidance model*

This system adopts the three-point method among classical guidance laws which belongs to the remote control guidance. The law of three-point guidance is to guide the missile centroid always on the connecting line between the radar guidance station and the target position in the process of attacking the target. The three-point method is simple and easy to implement in engineering, however, it takes disadvantages that when approaching the target the trajectory is more curved and the required normal overload increases rapidly, and when missile meets the low-altitude target the launch angle is small and the trajectory is low. According to the definition of the three-point method, the altitude and azimuth angles of the missile during flight are equal to the altitude and azimuth of the target. Therefore, the guidance equation for the three-point method is:

$$\varepsilon_M = \varepsilon_T, \beta_M = \beta_T \tag{1}$$

Where  $\varepsilon_M, \varepsilon_T$  are missile altitude and target altitude,  $\beta_M, \beta_T$  are missile azimuth and target azimuth.

Fig. 2 is plumb plane coordinate. We can get three point method of relative motion equations:



**Figure. 2** Plumb plane coordinate

$$\left. \begin{aligned} \frac{dR_M}{dt} &= V \cos \eta \\ R_M \frac{d\varepsilon_M}{dt} &= -V \sin \eta \\ \frac{dR_T}{dt} &= V_T \cos \eta_T \\ R_T \frac{d\varepsilon_T}{dt} &= -V_T \sin \eta_T \\ \varepsilon_M &= \theta + \eta \\ \varepsilon_T &= \theta_T + \eta_T \\ \varepsilon_M &= \varepsilon_T \end{aligned} \right\} \tag{2}$$

Where  $R_M$ ,  $R_T$  are missile range and target range,  $V$ ,  $V_T$  are missile velocity and target velocity,  $\theta$ ,  $\theta_T$  are missile trajectory tilt angle and target trajectory tilt angle,  $\eta$ ,  $\eta_T$  are missile lead angle and target lead angle. The line deviation of missile deviating from ideal trajectory is:

$$h_e = R_m(\varepsilon_m - \varepsilon_t) = R_m \Delta\varepsilon \tag{3}$$

In order to improve the altitude of the missile and prevent the overshoot of the missile too large from causing the danger of falling, the three-point method can be improved. We can lead into a initial preposition deviation  $\Delta\varepsilon_0$ .

Here,  $\Delta\varepsilon$  can be defined as:

$$\Delta\varepsilon = \Delta\varepsilon_0 e^{-K(1-\frac{R_m}{R_t})} \tag{4}$$

Where  $K$  is a constant. As the prefrontal deviation attenuated with time, the ballistic trajectory of the improved method is higher than that of the traditional three point method. Because the prefrontal deviation is positive, but its derivative is negative, and the required normal overload of missile reduces along with the decrease of the deviation. So, the trajectory of the improved method is more straight than the traditional three-point when approaching the target.

### 2.2 The missile model

For a general missile, the missile movement can be decomposed into longitudinal motion and lateral motion, and the decomposed longitudinal motion and lateral motion are independent of each other. To rolling missiles, due to the spin of the missile body, the symmetry plane of the missile body also spins. The attack angle and sideslip angle defined in body coordinate system will generate periodical alternations, thus the missile posture cannot be directly reflected. In body coordinate system, state variables, such as force and moment, attitude angle, also need to perform rolling projection. The kinematics equation is nonlinear and cannot be directly solved. The spin of the missile results in the cross coupling of the longitudinal and lateral movements of the missile, which mainly include the inertia coupling caused by the gyro effect, the aerodynamic coupling due to the Magnus effect, the control coupling caused by the steering engine delay, and the coupling caused by accelerometer not on the centroid. And the aerodynamic coefficients obtained from the wind tunnel tests in the equation of motion are difficult to describe in body coordinate system. Therefore, in order to describe the missile model, the quasi-body coordinate system and the quasi-velocity coordinate system need to be introduced. The definition of them can be found in [2]. The quasi-body coordinate system and the quasi-velocity coordinate system do not spin with the missile body. And can be linked with body coordinate system and velocity coordinate system by the spin transformation matrix  $H$ . The expression of  $H$  is:

$$H = \begin{bmatrix} \cos w_x t & \sin w_x t \\ -\sin w_x t & \cos w_x t \end{bmatrix} \tag{5}$$

The guidance problem of missile is described in inertial coordinate system. For a missile with an axisymmetric configuration, it can be considered that the body coordinate system is its inertial spindle system[3]. The equation of motion of a rolling missile in a projectile coordinate system can be described as:

$$\overset{g}{\dot{X}} = AX + B\delta \tag{6}$$

Where

$$X = \begin{bmatrix} w_{y_1} \\ w_{z_1} \\ \beta \end{bmatrix}; A = \begin{bmatrix} -a_1 & a_6 w_x & -a_2 & a_7 w_x \\ -a_6 w_x & -a_1 & -a_7 w_x & -a_2 \\ 1 & 0 & -a_4 & w_x \\ 0 & 1 & -w_x & -a_4 \end{bmatrix}; B = \begin{bmatrix} -a_3 & 0 \\ 0 & -a_3 \\ -a_5 & 0 \\ 0 & -a_5 \end{bmatrix} \tag{7}$$

Where  $w_x$  is the body angular velocity of rotation,  $w_{y_1}$ ,  $w_{z_1}$  are the projection component of the body angular velocity of rotation in body coordinate system,  $\alpha$ ,  $\beta$  are the attack angle and sideslip angle defined in body coordinate system,  $\delta$  is rudder angle,  $a_1 \sim a_7$  are dynamic coefficients whose definition are in [4].

Derivation of state equation in quasi-body coordinate system from the state equation in body coordinate system, we can define

$$\mathbf{X}^* = [w_{y4} \quad w_{z4} \quad \beta^* \quad \alpha^*]^T, \mathbf{H} = \begin{bmatrix} \mathbf{H} & \mathbf{0} \\ \mathbf{0} & \mathbf{H} \end{bmatrix} \quad (8)$$

Where  $\mathbf{X}^*$  is state variable in quasi-body coordinate system.

Thus,

$$\dot{\mathbf{X}} = \mathbf{H}\mathbf{X}^* \quad (9)$$

Substituting equation (9) into equation (6), we can get

$$\dot{\mathbf{X}}^* = [\mathbf{H}^{-1}\mathbf{A}\mathbf{H} - \mathbf{H}^{-1}\mathbf{H}]\mathbf{X}^* + \mathbf{H}^{-1}\mathbf{B}\delta \quad (10)$$

It can be proved that[3]

$$\mathbf{H}^{-1}\mathbf{A}\mathbf{H} = \mathbf{A}, \mathbf{H}^{-1}\mathbf{B} = \mathbf{B}\mathbf{H} \quad (11)$$

Substituting equation (11) into equation (10), we can get

$$\dot{\mathbf{X}}^* = (\mathbf{A} - \mathbf{H}^{-1}\mathbf{H})\mathbf{X}^* + \mathbf{B}\mathbf{H}\delta \quad (12)$$

In addition

$$\delta = \mathbf{H}\delta^* \quad (13)$$

So

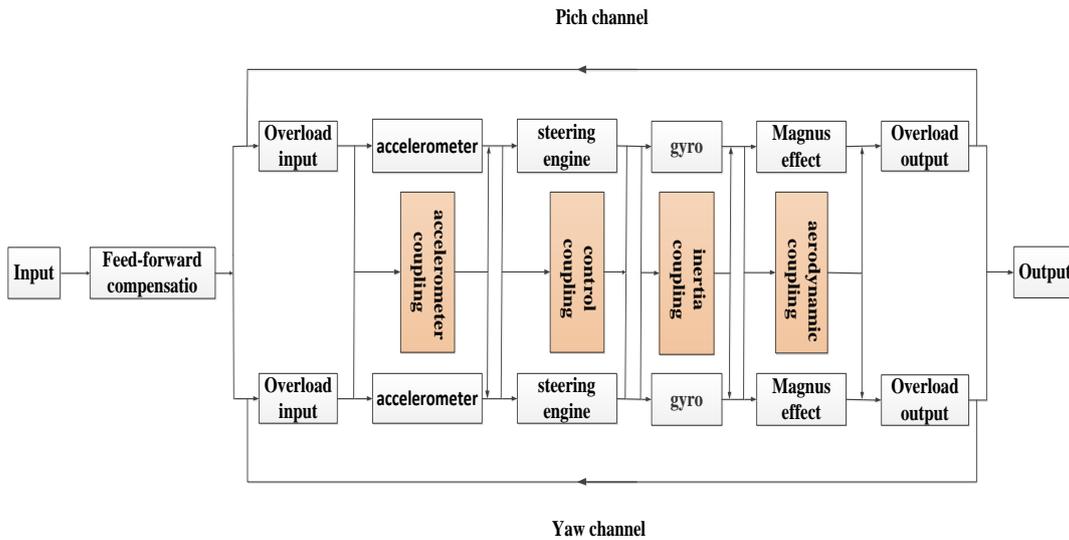
$$\dot{\mathbf{X}}^* = (\mathbf{A} - \mathbf{H}^{-1}\mathbf{H})\mathbf{X}^* + \mathbf{B}\delta^* \quad (14)$$

The equation (14) is the state equation of pitching-yaw channels in quasi-body coordinate system.

### 2.3 The stability control model

From Section 2.2, it can be known that there are cross couplings in the pitch-yaw channels' state equation of rolling missile. In addition, the steering engine segment and the accelerometer pre-segment will also be coupled from body coordinate system spin to quasi-body coordinate system. So, it is necessary for the control system to perform decoupling control. For the rolling channel, it only need to be stable but not controlled.

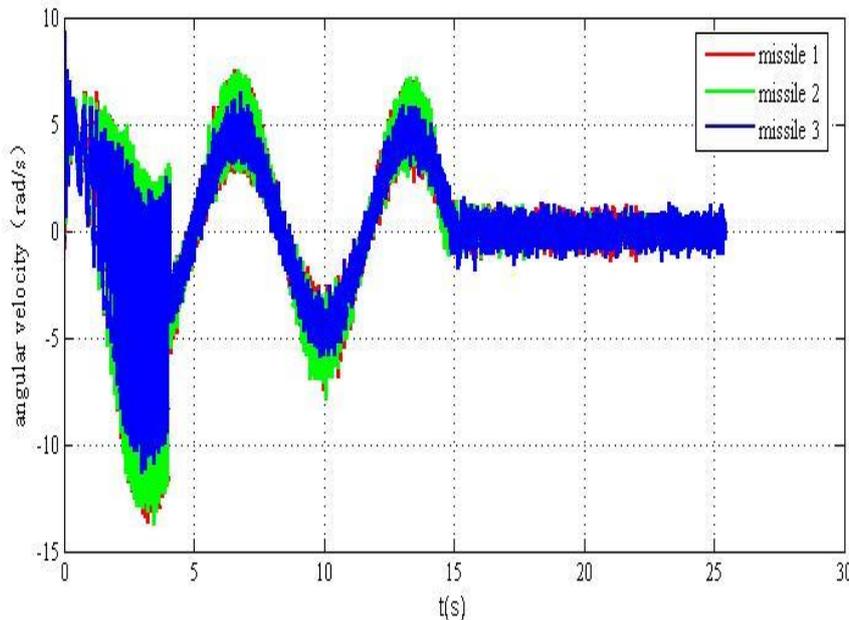
To achieve decoupling control of pitch-yaw channels, that is essentially diagonalization of the transfer function described by the state equation. The feed-forward compensation method could be used to decouple the system. The decoupling principle is illustrated in Figure 3, the specific design method is referred to [5].



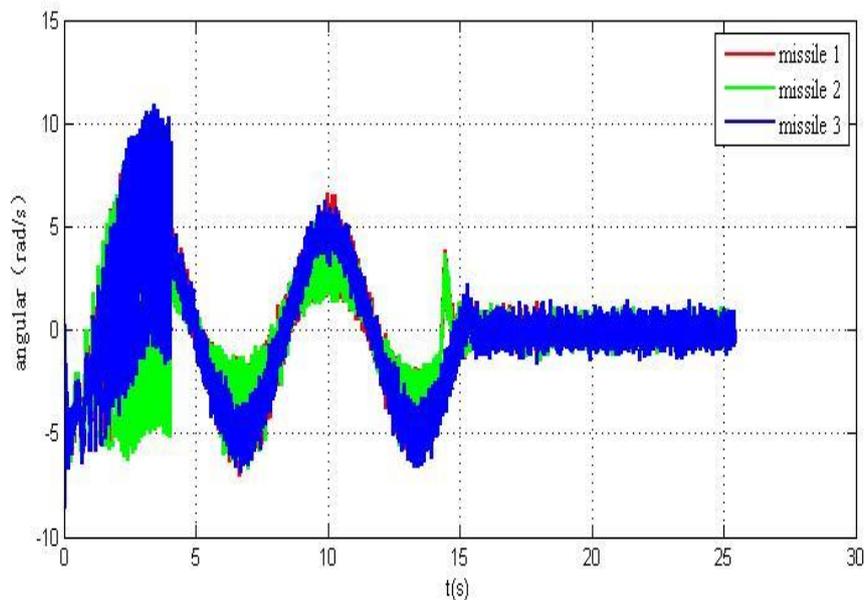
**Figure 3.** Pitch-yaw channels decoupling of rolling missile

**3 HILS and simulation result**

To verify the correctness of the scheme of multiple projectile for rolling missiles, the HILS with damping gyros of pitch-yaw channels is to be performed. The HILS is set as follows: Missile 1 uses photoelectric tracking radar mode, added initial interference whose boundary value is (-0.5, 0.5) rad/s in damping gyro. Missile 2 uses phased array radar mode, added separation interference whose boundary value is (-0.5, 0.5) rad/s in damping gyro. Missile 3 uses double radar mode, no interference. Target flight speed is 150m/s. The position of the target when the missiles launch is (13000m, 3000m, 0). Attack mode is counterpunch. The simulation result is as follows:



**Figure 4.** Data of pitch channel.



**Figure 5.** Data of yaw channel.

According to Fig. 4 and Fig. 5, we can see that the rolling channel and the yaw channel are decoupled. The amplitudes of the pitch channel and the yaw channel are basically same and the phases are opposite, which shows the pitch control and the yaw control have symmetry. The HILS result has no lost frames and false frames, which reflects the stability and reliability of the system. But it can be seen that there is a bigger deviation in the yaw channel than the pitch channel. At missile 2 separation time (14.5s), the yaw channel appears jumping faults .

#### 4 Conclusion

A multiple projectiles weapon system scheme for air-defense rolling missiles is put forward in this paper in view of this problem which a missile hard to hit an target independently. The guidance model, the missile model and the stability control model are briefly analyzed. The HILS result shows that rolling channel and the yaw channel are decoupled and no lost frames and false frames in the simulation cycle, which reflects the correctness and stability of the scheme. At present, this scheme has been applied to engineering practice.

#### References

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