Bounded Differential Game Guidance Law for Interceptor Missiles with Aero Fins and Reaction Jets

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A differential game guidance law for an endoatmospheric interceptor missile steered by aero fins and reaction jets is developed in this paper with bounded controls. For a low-altitude endoatmospheric interceptor, the propellant of the reaction-jet control system (RCS) is restricted by the missile configuration. Considering propellant limits, the effect of the RCS thrust on homing performance is investigated through game space structures. Also, to use the RCS at an appropriate timing, game space decomposition is used to determine the initiating time of the RCS. Finally, the effectiveness of the guidance law is demonstrated by a realistic ballistic missile defense scenario. It is shown that the proposed guidance law provides a significant improvement in homing accuracy compared to the conditional one. Furthermore, under propellant limits, a bigger RCS thrust cannot guarantee a higher homing accuracy.

Key Words: Differential Game, Guidance, Interceptor Missile, Reaction Jet, Game Space

Nomenclature

\[ V \]: velocity
\[ X \]: state vector
\[ r \]: range
\[ a \]: realized acceleration
\[ a_{\text{max}} \]: maximum acceleration
\[ d^e \]: acceleration of interceptor body
\[ u \]: missile acceleration command
\[ v \]: target acceleration command
\[ d \]: direct lift coefficient
\[ t \]: time
\[ y \]: relative displacement
\[ \Delta t \]: RCS maximum operation time
\[ t_{\text{RS}} \]: RCS starting work time
\[ t_{\text{RE}} \]: RCS ending work time
\[ Z \]: zero effort miss distance
\[ \theta \]: flight-path angle
\[ \lambda \]: angle of line of sight
\[ \mu \]: maneuverability ratio
\[ \varepsilon \]: dynamics ratio

Subscripts

0: initial
f: final
P: interceptor (pursuer)
E: target (evader)
T: tail
J: reaction-jet control system
PT: tail of interceptor
PJ: RCS of interceptor

1. Introduction

The mission of tactical ballistic missile (TBM) defense presents new challenges for interceptor missiles. To provide a hit-to-kill homing accuracy in this scenario, both maneuverability and agility are required for a low-altitude endoatmospheric interceptor. In general, high maneuverability of the missile can be achieved by aerodynamic control only. However, to obtain high agility, it is necessary to use the reaction-jet control system (RCS). There are two types of RCS configuration: divert and moment.1) This paper will investigate the latter, where the RCS is located ahead of the center of gravity and produces force and moment in the pitch axis.

Currently, interceptors always follow the conventional proportional navigation (PN) guidance law using aerodynamic control until the RCS is initiated to increase the agility of the interceptor at the end of the homing phase. The RCS can greatly reduce the time constant of the guidance loop, but also introduces one more degree of freedom. This additional degree of freedom requires special consideration in the guidance and control system. Unfortunately, in previous studies,2,3) the focus is on autopilot design. As a consequence, high homing accuracy can only be achieved for non-maneuvering targets. If the targets have high maneuverability the miss distance will never be zero.4) The discrepancies between these results can be attributed to insufficient use of the interceptor’s maneuverability and inappropriate initiating timing of the RCS. Therefore, improved guidance laws seem necessary.

At interception of a maneuvering TBM, the target’s maneuver is unknown to the interceptor. Thus, the scenario should be formulated as a zero-sum pursuit evasion game.5) Gutman investigated a scenario between two players assuming first-order pursuer dynamics and ideal evader...
dynamics. Based on realistic TBM flight conditions, the scenario was then extended to include time-varying velocities and inherent estimation delay. In all the above scenarios only a single actuator is considered, so guidance laws cannot be applied by interceptors with dual control systems. Recently, an end-game guidance strategy tailored for an air-to-air missile with forward and aft control system was presented. Nevertheless, it still cannot be directly utilized by low-altitude endoatmospheric interceptors due to different characters between the canard and reaction jet.

This paper focuses on designing a differential game guidance law for a low-altitude endoatmospheric interceptor steered by aerodynamic tails and forward RCS during the terminal homing phase. The purpose is to utilize the maneuverability of the interceptor sufficiently and to determine the optimal distribution of guidance commands between aero fins and reaction jets. Moreover, for a low-altitude endoatmospheric interceptor, the propellant of the RCS is restricted by the missile configuration. Although increasing the RCS thrust can increase the agility of the interceptor, it also decreases the maximum operation time of the RCS. Therefore, the effect of RCS thrust on homing performance should be investigated for practical applications. Similarly, since the maximum working time is constrained, the appropriate timing to initiate the terminal RCS should be discussed. Taur analyzed this problem through extensive mathematical simulations, whereas game space decomposition is used in this study.

2. Problem Formulation

The investigated interception scenario is the terminal homing phase of a low-altitude endoatmospheric interceptor missile launched against a re-entry TBM with high maneuverability. To simplify the equations of motion, the following assumptions are made in common with many preceding studies:

1) The guidance problem can be treated as a planar engagement.
2) The relative end-game trajectory can be linearized around the initial line-of-sight (LOS).
3) The velocities of the interceptor and target are constant in magnitude.
4) Both missiles can be represented by point-mass models.
5) The interceptor has perfect information on the target.

The geometry of the end game in the pitch plane is shown in Fig. 1, where the X-axis is aligned with the initial LOS.

2.1. Dynamic models

The closed-loop maneuvering dynamics of the pursuing interceptor is approximated by two first-order transfer functions:

\[
\frac{a_p}{u_t} = \frac{1}{\tau_1 s + 1}, \quad d_t < 0
\]  

As known, RCS actuators can be modeled by first-order transfer functions. Since the RCS thrust does not produce instantaneous maneuvering acceleration, there is no direct lift coefficient in Eq. (2). Additionally, the RCS reduces the time constant, and thus \( \tau_1 \) is smaller than \( \tau_T \). The total acceleration of the interceptor is:

\[
a_p = a_{p_T} + a_{p_J}
\]  

To avoid control saturation, it is assumed that:

\[
|u_T| \leq \alpha \cdot a_p^{\text{max}}, \quad 0 \leq \alpha \leq 1
\]  

\[
|u| \leq \beta \cdot a_p^{\text{max}}, \quad 0 \leq \beta \leq 1
\]  

The overall acceleration command should not exceed the maximum maneuvering capability of the interceptor.

Furthermore, taking maneuverability of the interceptor explicitly into account, \( \alpha \) and \( \beta \) must satisfy:

\[
\alpha + \beta = 1
\]  

Letting \( \beta \to 0 \), the interceptor will be controlled only by the aerodynamic system.

Based on assumption (4), the maneuvering dynamics of the target is approximated by:

\[
\frac{a_E}{v} = \frac{1}{\tau_E s + 1}
\]  

Moreover, we assume control of the target is bounded by:

\[
|u| \leq a_E^{\text{max}}
\]  

The maneuverability ratio and dynamics ratio between the pursuer and the evader are defined as:

\[
\mu = \frac{a_p^{\text{max}}}{a_E^{\text{max}}}
\]

\[
\epsilon = \frac{\tau_1}{\tau_T}
\]

The product of these two parameters is called the pursuer-evader agility ratio.

2.2. Game model

Based on assumptions (2) and (3), the final time of the interception can be computed by:

\[
t_f = \frac{r_0}{V_C}
\]  

defining the time-to-go as:
\[ t_{go} = t_f - t \] (12)

The state vector associated with the linearized relative motion normal to the initial LOS is:

\[ X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix}^T \]
\[ = \begin{bmatrix} y & \dot{y} & a_E & \dot{a}_E^b & \dot{a}_E^b \end{bmatrix}^T \] (13)

The state equation of motion is described by:

\[ \dot{X}(t) = AX(t) + Bu(t) + Cv(t) \] (14)

where

\[ A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & 0 & -1/\tau_E & 0 & 0 \\ 0 & 0 & 0 & -1/\tau_T & 0 \\ 0 & 0 & 0 & 0 & -1/\tau_T \end{bmatrix} \] (15a)

\[ B = \begin{bmatrix} 0 & 0 \\ -d_T & 0 \\ 0 & 0 \\ (1 - d_T)/\tau_T & 0 \\ 0 & 1/\tau_T \end{bmatrix} \] (15b)

\[ C = \begin{bmatrix} 0 & 0 & 1/\tau_E & 0 & 0 \end{bmatrix}^T \] (15c)

The miss distance is chosen as the cost function:

\[ J = |DX(t_f)| = |x_1(t_f)| \] (17)

where

\[ D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \] (18)

Based on the transition matrix for the original homogeneous system of Eq. (14):

\[ \Phi(t_f, t) = L^{-1}[(sI - A)^{-1}] \]

\[ = \begin{bmatrix} 1 & t_{go} \tau_E^2 \psi(t_{go}/\tau_E) \\ 0 & 1 \tau_E \psi(t_{go}/\tau_E) \\ 0 & 0 \exp(-t_{go}/\tau_E) \\ 0 & 0 \exp(-t_{go}/\tau_T) \\ 0 & 0 \end{bmatrix} \] (19)

where

\[ \psi(\xi) = e^{-\xi} + \xi - 1 \] (20)

\[ \phi(\xi) = 1 - e^{-\xi} \] (21)

we obtain the transformation of the well-known zero effort miss (ZEM):

\[ Z(t) = D \cdot \Phi(t_f, t) \cdot X(t) \]
\[ = x_1(t) + x_2(t)t_{go} + x_3(t)\tau_E^2 \psi(t_{go}/\tau_E) - x_4(t)\tau_T^2 \psi(t_{go}/\tau_T) \] (22)

Then, vector equation (Eq. (14)) can be reduced to a scalar dynamic equation:

\[ \dot{Z}(t) = \tau_E f(0, t_{go}/\tau_E) - \tau_T f(d_T, t_{go}/\tau_T)u_T \]
\[ - \tau_f f(0, t_{go}/\tau_T)u_f \] (23)

where

\[ f(\delta, \zeta) = \delta \cdot \zeta + (1 - \delta) \cdot (e^{-\zeta} + \zeta - 1) \] (24)

Simultaneously, the cost function given in Eq. (17) is replaced by:

\[ J = |Z(t_f)| \] (25)

3. Game Solution

3.1. Necessary optimality conditions

The Hamiltonian of the problem is:

\[ H = \lambda_Z(t) [\tau_E f(0, t_{go}/\tau_E) - \tau_T f(d_T, t_{go}/\tau_T)u_T \]
\[ - \tau_f f(0, t_{go}/\tau_T)u_f] \] (26)

The optimal strategies satisfy:

\[ u_T^* = a a_{p_T}^\text{max} \text{sign}[\lambda_Z(t) \cdot f(d_T, t_{go}/\tau_T)] \] (27)

\[ u_f^* = a a_{p_f}^\text{max} \text{sign}[\lambda_Z(t) \cdot f(0, t_{go}/\tau_T)] \] (28)

\[ v^* = a_E^\text{max} \text{sign}[\lambda_Z(t)] \cdot f(0, t_{go}/\tau_E) \] (29)

where \( \lambda_T \) is the co-state variable satisfying

\[ \dot{\lambda}_z = -\frac{\partial H}{\partial Z} = 0 \] (30)

\[ \lambda_Z(t_f) = \text{sign}[Z(t_f)], \quad \forall Z(t_f) \neq 0 \] (31)

which means that

\[ \lambda_Z(t) = \text{sign}[Z(t)], \quad \forall Z(t) \neq 0 \] (32)

Using Eq. (32) and noting \( f(\delta, \zeta) > 0, \forall \delta \in (0, 1), \zeta > 0 \), the optimal strategies become:

\[ u_T^* = a a_{p_T}^\text{max} \text{sign}[Z(t)] \cdot \text{sign}[f(d_T, t_{go}/\tau_T)] \] (33)

\[ u_f^* = a a_{p_f}^\text{max} \text{sign}[Z(t)] \] (34)
Substituting Eqs. (33)–(35) into Eq. (23) yields the optimized dynamics of this game:

$$v^* = a_{Ei}^{\text{max}} \, \text{sign}(Z(t_i))$$

(35)

Thus, the game is constant:

$$\frac{dZ^*}{dt} = \Gamma(t_i, t) \cdot \text{sign}(Z(t_i)), \quad Z(t_i) \neq 0$$

(36)

where

$$\Gamma(t_i, t) = \tau_E a_{Ei}^{\text{max}} f(0, t_{go}/\tau_E) - \tau_T \alpha_{p}^{\text{max}} [f(d_T, t_{go}/\tau_T)]$$

$$- \tau_T \beta a_{p}^{\text{max}} f(0, t_{go}/\tau_T)$$

(37)

When the interceptor is steered only by the aerodynamic control system, $\beta$ is equal to zero. Removing the effect of the RCS leads Eqs. (36)–(37) to:

$$\frac{dZ}{dt} = \Gamma_a(t_i, t) \cdot \text{sign}(Z(t_i)), \quad Z(t_i) \neq 0$$

(38)

$$\Gamma_a(t_i, t) = \tau_E a_{Ei}^{\text{max}} f(0, t_{go}/\tau_E) - \tau_T \alpha_{p}^{\text{max}} [f(d_T, t_{go}/\tau_T)]$$

(39)

### 3.2. Game space structure

During the terminal homing phase of the interception, the velocity of the TBM remains almost unchanged. As a consequence, the maneuverability of the TBM increases due to the higher air density at lower altitudes. This may cause $\Gamma_a(t_i, t)$ to change its sign. Without loss of generality, here we assume that it changes only once. Therefore, the case selected for investigation is the one where the interceptor does not have an agility advantage over the target but has a maneuverability advantage using aerodynamic control only.

The maximum operation time of the RCS, $\Delta t$, satisfies:

$$t_{BS} = t_{RS} + \Delta t$$

(40)

Since the RCS is initiated at the end of the terminal homing phase, we assume that $t_{BS}$ is equal to $t_t$. Thus, the RCS initiating time $t_{RS}$ can be calculated. When $t \leq t_{RS}$, the interceptor is steered only by the aerodynamic control system.

The game space is obtained by integrating Eq. (36) backward from any given end condition $Z(t_f)$. The optimal trajectories shown in Fig. 2 are the borders between the two regions of the different game solutions $D_0$ and $D_1(D_1^+ \cup D_1^-)$. Inside these two optimal boundary trajectories, $Z_1^+$ and $Z_1^-$, there is a region $D_0$, defined by:

$$|Z(t)| < Z_1^+(t)$$

(41)

In $D_0$, the optimal strategies are not unique, and the value of the game is constant:

$$J^*_0 = 0$$

(42)

This means that a perfect interception of the evader can be guaranteed against any feasible evasive maneuver.

The other region outside these boundaries is denoted by $D_1$ and defined as:

$$|Z(t)| \geq Z_1^+(t)$$

(43)

$D_1$ is a regular region, where the optimal strategies are given by Eqs. (33)–(35). The value of the game is a function of the initial conditions:

$$J^*_1 = |Z_0| + \int_{t_0}^{t_1} \Gamma(t_i, t) \, dt$$

(44)

Thus, perfect interception cannot be guaranteed.

For comparison, the optimal boundary trajectories using only aerodynamic control are also shown in Fig. 2. Note that these boundary trajectories reach the $Z = 0$ axis at $t = t_t$, which is the solution of $\Gamma_a(t_i, t) = 0$. Every trajectory starting from $D_0$ must go through the throat ($Z(t) = (0, t_t)$). Consequently, the value of the game for this entire region is constant:

$$M_s = \int_{t_0}^{\infty} \Gamma_a(t_i, t) \, dt$$

(45)

In addition, there is a region $D_1^+$ where the miss distance is dominated by the target’s maneuver, and a zero miss distance can no longer be achieved.

Compared to aerodynamic control without RCS, a dual control system can significantly improve homing performance. Instead of the guaranteed perfect interception, it can also relax the handover conditions between the midcourse and the terminal homing phase.

### 3.3. Effect of parameters

Increasing the RCS thrust increases the contribution of the RCS to the interceptor acceleration. Neglecting propellant limits, Fig. 3 shows the effect of the acceleration contribution $\beta$ on game space structures, when keeping $a_{Ei}^{\text{max}}$ constant.

Obviously, increasing the acceleration contribution $\beta$ leads to an increase in region $D_0$ and a decrease in region $D_1$, improving homing performance, and the handover conditions between the midcourse and terminal phase are relaxed, as expected. The RCS has similar capability to a canard, but its effectiveness is independent of flight conditions such as angle-of-attack (AOA) and dynamic pressure.

### 4. Propellant Limits

The RCS propellant is restricted by the configuration of the interceptor, such as weight and size. Here, the effects of the RCS thrust on game space structures are investigated under propellant limits. As known, there are complex rela-
tionships between the magnitude of thrust, working time, and acceleration contribution. Although increasing RCS thrust decreases the maximum operation time $\Delta t$, it can also increase the acceleration contribution $\beta$. Assuming $\tau_1$ is constant, the values of $\beta$ and corresponding $\Delta t$ are listed in Table 1.

4.1. Control thrust

Based on the above assumptions, the effects of the RCS thrust on game space structures are presented in Fig. 4. Note that, as expected, a big $\beta$ can enlarge the region $D_0$ more effectively at the end of the terminal homing phase, and is more effective for a short interception time. However, the shortened work time restricts its influence. A small $\beta$ can create the maximum value of $ZEM(t_{go})$ and is more useful in relaxing the handover conditions between the midcourse and terminal phase. In contrast, the conditions for perfect interception become critical, especially at the end of the terminal phase. Obviously, increasing the control thrust of the RCS cannot always improve the homing performance under propellant limits. When the target has high maneuverability, this trend becomes more evident, as shown in Fig. 5.

For comparison, the optimal boundary trajectories using only aerodynamic control are given in Fig. 5. Because of the increased maneuverability of the target, the extremum time $t_s$ becomes a large value in this case, and the region $D_1^{*}$, dominated by the target’s maneuver, enlarges too. As can be seen, all the trajectories are roughly the same before $t_s$. The differences after $t_s$ can be attributed to the effect of the RCS, which is implemented to decrease the value of the game $M_s$ and eliminate the region $D_1^{*}$. With $\beta = 0.75$, the effect of the RCS is constrained due to the restriction of the short operation time. $M_s$ is still a large value and perfect interception cannot be achieved. With $\beta = 0.25$, $M_s$ can be reduced to a small value. However, the region of satisfying the conditions is small, so excellent performance cannot be guaranteed. With $\beta = 0.5$, the effect is compromised between the above two cases. $M_s$ can be reduced to a small value, and the region for satisfying the conditions is increased too.

Consequently, the phenomenon of improving the homing performance through the increased RCS thrust appears only with sufficient propellant. With limited propellant, bigger RCS thrust cannot guarantee higher homing accuracy, which is demonstrated later. For practical applications, a trade-off between RCS thrust and the operation time should be considered, and an optimization method for RCS thrust is also needed. These will be left to future discussion.

4.2. Initiating time

Due to operation time limits, the appropriate timing to initiate the RCS should also be analyzed for practical applications.

Choose different values of $t_{RE}$ as:

$$t_0 < t_{RE} < t_s, \quad t_s < t_{RE} < t_t, \quad t_{RE} = t_t$$

(46)

The boundary trajectories are presented in Fig. 6 to decompose the game space. The bold lines are the boundary...
trajectories using aerodynamic control only, as shown in Fig. 2.

From Fig. 6, region $D_0$ is increased in all three cases compared to only aerodynamic control. However, the perfect interception can only be guaranteed at $t_{RE} = t_I$. With $t_0 < t_{RE} < t_s$, every trajectory starting from $D_0$ still must go through the throat $(Z, t) = (0, t_s)$, and the final value of the game is the constant $M_s$. So there is no improvement in this case if the miss distance is selected as the cost function. With $t_s < t_{RE} < t_I$, the trajectory starting from $D_0$ will also go through a throat, but the final value of the game $M_s$ becomes smaller. When $M_s < 1$, a direct hit can be achieved. Therefore, in this case, it is possible to guarantee effective interception, and there is adequate time remaining to stabilize the airframe.

When RCS thrusters are used for control there is an interaction between the jet plume and the external supersonic flow. This results in model uncertainties, thereby causing extremely serious robust problem, and even making the airframe unstable. Hence, there adequate time should be left to control the airframe to be stable, if the RCS is used. Since the case of $t_{RE} = t_I$ does not allow enough time to control the airframe, it is not suitable for the RCS. To achieve an effective interception and to keep the airframe stable, the most appropriate time to initiate the RCS is:

$$t_s < t_{RE} < t_I$$  (47)

For practical applications, a trade-off between homing performance and airframe stability should be made.

5. Simulation Study

The feedback form of the bounded differential game guidance law presented in this paper is:

$$u_f^* = \alpha\theta_{\text{max}} \cdot \text{sign}[Z(t)] \cdot \text{sign}[f(d_T, t_{go}/\tau_T)]$$  (48)

$$u_r^* = \beta\theta_{\text{max}} \cdot \text{sign}[Z(t)]$$  (49)

In this section, the validity of the guidance law is tested using a two-dimensional realistic ballistic missile defense scenario against a highly maneuvering TBM. The selected maneuver sequence of the TBM is a bang-bang type. In practice, the blind target has no information about the interceptor, so it will switch its maneuvering direction randomly. The parameters of the simulations are given in Table 2.

### 5.1. Differential game guidance law

The following denotes the bounded differential game guidance law presented in this paper as BDGL. The BDGL miss distance is shown in Fig. 7 as a function of the target maneuver switching time $t_{SW}$. For comparison, the miss distance obtained only by the aerodynamic control is also given. Note that there is a significant improvement in the homing performance with the help of RCS. The miss distance is near zero repeatedly, and perfect interception can be guaranteed. In the conventional method, the miss distance is always bigger than 30 m. It is too large compared to the BDGL case, so Fig. 7 does not give the result. The advantage of BDGL can be attributed to its effective utilization of the interceptor’s maneuver-ability and agility.

### 5.2. Initiating time

The effects of different initiating times on the homing performance are studied here. Figure 8 shows the miss distance vs. different target maneuver switching time $t_{SW}$. As can be seen, the case of $t_{RE} = t_I$ provides the best homing accuracy, and the perfect interception can be guaranteed. With $t_0 < t_{RE} < t_s$, the interceptor has the least successful homing accuracy. In this case, the final miss distance is dominated by the target’s maneuver, and perfect interception cannot be obtained in most cases. With $t_s < t_{RE} < t_I$, the interceptor has a homing performance between the former two cases. Because the final miss distance can
always be reduced to less than 1 m, an effective interception can be obtained. This indicates that the initiating time of Eq. (47) is feasible.

5.3. Control thrust
The effects of the RCS thrust on homing performance, with $a_{E_{\text{max}}} = 20\, g$ and $a_{E_{\text{max}}} = 24\, g$, are shown in Fig. 9 and Fig. 10, respectively. It is obvious that high homing accuracy can always be achieved with $a_{E_{\text{max}}} = 20\, g$. On increasing $a_{E_{\text{max}}}$ to 24 g, although the highest homing accuracy is still obtained at $\beta = 0.75$, the miss distance is larger than 1 m in most cases, and high homing performance cannot be guaranteed. At $\beta = 0.25$, there is almost no possibility of effective interception. High homing performance can be guaranteed only at $\beta = 0.5$. In this case, the miss distance is always smaller than 1 m, and the hit-to-kill homing accuracy can be realized.

These results show that increasing RCS thrust does not always obtain high homing accuracy with propellant limits. Once again, a trade-off between control thrust and operation time must be made for practical applications.

6. Conclusions
This paper develops a bounded differential game guidance law for a low-altitude endoatmospheric interceptor missile with aero fins and reaction jets. The guidance law utilizes the maneuverability of the interceptor effectively, and can determine the optimal distribution of acceleration commands between the two control channels. Therefore, there is a significant improvement in homing accuracy compared to conventional methods.

For a low-altitude endoatmospheric interceptor, the RCS propellant is restricted. Increasing RCS thrust decreases operation time, but also increases the acceleration contribution. Game space structures were used to investigate the effect of RCS thrust on homing performance. It was shown and confirmed via simulations that, under propellant limits, a bigger RCS thrust cannot guarantee higher homing performance, especially when the target has high maneuverability. Therefore, development of an optimization method for RCS thrust is required.

Fig. 8. Miss distance with different initiating time.

Fig. 9. Miss distance with different $\beta$ when $a_{E_{\text{max}}} = 20\, g$.

Fig. 10. Miss distance with different $\beta$ when $a_{E_{\text{max}}} = 24\, g$.

The appropriate timing to initiate the RCS was also investigated through the game space structure. For practical applications, it is necessary to make a trade-off between homing performance and airframe stability.

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