Guidance Design for Vertical Launch Missiles

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Abstract—In this work, a fuzzy logic-based guidance design to deal with the problem is addressed for longer engagement time and beneficial interception attitudes. The integrated fuzzy logic-based guidance scheme consisting of vertical, midcourse and terminal guidance phase is capable of intercepting the target from diverse incoming aspects. The engagement strategy in vertical guidance phase includes general vertical launch and vertical launch with back turn (BT) which is deal with the cases of longer and shorter engagement ranges respectively.

Keywords — Guidance and Control, Fuzzy logic control, Vertical guidance, Ballistic target, Missile.

I. INTRODUCTION

Development of guidance laws for surface-to-air missiles to against very high speed targets has been studied and investigated in recent year. When a ballistic target reenters the atmosphere, its speed is very high and remaining time to ground impact is relatively short. From the results of previous study [1,2], it has been a principle that the optimal trajectory to intercept a ballistic target is to construct a near head-on scenario to achieve a direct hit. Using this setting, it may ultimately hit the target without resorting to excessive lateral acceleration. In the past, the guidance designs based on the line-of-sight (LOS) angle rate were found to be effective for targets with speed far lower than the pursuit missile and acceptable miss distances (MD) were usually obtainable. However, new generation targets possess higher speed and larger maneuverability. Classical guidance laws are no longer effective to engage that kind of targets [3].

In the literature, several guidance design techniques such as linear quadratic regulator (LQR) [4], explicit guidance [5] and modified proportional guidance [6] have been proposed for implementation of the optimal guidance law. In particular, LQR [2], modified explicit guidance [7] and has been applied to deal with the anti-tactical ballistic missile (ATBM) guidance design problem. However, solving LQR problems in real time is known to be practically infeasible in most cases.

Base on the feasible and easy realizable requirements, a fuzzy system possesses a simpler structure than the traditional trajectory shaping guidance and doesn’t demand on the precise modeling knowledge. Furthermore, realization of a fuzzy inference system is easy enough to minimize the work load of the airborne computer. Recently, researchers have attempted to apply it to the missile guidance designs [8,9]. In our previous study [10,11], an integrated fuzzy type guidance law was exploited for an effective engagement strategy of ballistic targets with a slanted launch interceptor. However, compared to the case of slanted launch, a vertical launch interceptor possesses extra advantages that are worthy of more attention. That means the launcher needs not to be rotated to aim the incoming target before interceptor launch and it is capable of intercepting targets that fall into the zone that the slanted launch interceptor couldn’t reach.

In this paper, two vertical launch guidance laws: (i) general vertical launch and (ii) vertical launch with back turn (BT) are developed with respect to different engagement scenarios. Case (i) applies for the longer engagement range in which the vertical launch guidance law involves the shaping, midcourse and terminal phases. Case (ii) applies for the shorter engagement range in which the vertical launch with BT is combined with the terminal phase to extend the defensible volume which the slanted launch can’t deal with.

II. SYSTEM DESCRIPTIONS

A. INTERCEPTOR

Consider the 3D translational equations of motion of the guided missile:

\[ \dot{v}_m = (T \cos \alpha - D) / m - g \sin \gamma, \quad v_m(0) = 0 \]  
\[ \dot{\gamma} = (L + T \sin \alpha) \cos \phi / (m v_m) - g \cos \gamma / v_m, \quad \gamma(0) = \gamma_0 \]  
\[ \dot{\psi} = (L + T \sin \alpha) \sin \phi / (m v_m \cos \gamma), \quad \psi(0) = \psi_0 \]  
\[ \dot{x}_m = v_m \cos \gamma \cos \psi, \quad x_m(0) = x_{m0} \]  
\[ \dot{y}_m = v_m \cos \gamma \sin \psi, \quad y_m(0) = y_{m0} \]  
\[ \dot{h}_m = v_m \sin \gamma, \quad h_m(0) = h_{m0} \]

where \( m \) is the missile mass, \( T \) is the thrust, \( \gamma \) is the flight-path angle, \( \psi \) is the azimuth angle, the lift force is \( L = (\sigma v_m^3 s_m C_{l\alpha}) / 2 \) and the drag force is \( D = (\sigma v_m^3 s_m C_{\mu \alpha}) / 2 \) with \( C_{l\alpha} = C_{l\alpha,0}(\alpha - \alpha_0) \) and \( C_{\mu \alpha} = C_{\mu \alpha,0} + \mu C_{l\alpha} \). \( C_{l\alpha,0} \) and \( C_{\mu \alpha,0} \) and \( \mu \) are given as functions of Mach number, which is the function of the velocity \( v_m \) and the altitude \( h_m \). Referring to Fig. 1, the aforementioned angle-of-attack \( \alpha \) and rolling angle \( \phi \) are treated as the control variables on the vertical and the horizontal plane guidance laws, respectively.
B. TARGET

The target vehicle in the reentry phase over a flat, non-rotating earth with constant gravity is considered. The ballistic target model in radar coordinates centered at radar site is assumed as

\[ \dot{v}_t = -\frac{\rho v_t^2}{2\beta} g \cos \gamma \sin \gamma + a_n, v_t(0) = v_{t0} \]

\[ \dot{v}_h = -\frac{\rho v_h^2}{2\beta} g \cos \gamma \sin \gamma + a_{\beta}, v_h(0) = v_{h0} \]

\[ \dot{v}_m = -\frac{\rho v_m^2}{2\beta} g \sin \gamma - g + a_m, v_m(0) = v_{m0} \]

where \( v_{tx}, v_{ty}, v_{ta} \) denote the velocity components of \( v_t \) in the \( X, Y \) and \( H \) axes, respectively; \( a_n(t) \), \( a_{\beta}(t) \) and \( a_m(t) \) are the uncertain accelerations due to maneuvering; the flight path angles \( \gamma_t \) and \( \gamma_h \) and the ballistic coefficient \( \beta \) are given as

\[ \gamma_t(t) = \tan^{-1}\left(\frac{v_{tx}}{\sqrt{v_{ty}^2 + v_{ta}^2}}\right) \]

\[ \gamma_h(t) = \tan^{-1}\left(\frac{v_{ty}}{v_{ta}}\right), \text{ and } \beta = \frac{W}{s_t C_{d0}} \]

where \( s_t \) \( W \) and \( C_{d0} \) represent the reference area, weight and zero-lift drag coefficient of the ballistic target, respectively.

III. ENGAGEMENT STRATEGY

The proposed engagement strategy is divided into two schemes depended on the interceptor-target relative range and height. For the case of general vertical launch guidance (GVLG), the interceptor-target relative range are long enough for the guidance system to complete four guidance phases, i.e. vertical, midcourse, shaping and terminal guidance phases. For the case of vertical launch with back-turn guidance (VLBG), the target has already come close to the interceptor’s launcher, there is short of sufficient distance for it to build speed and pose itself for effective engagement. Vertical and terminal guidance phases are proposed to deal with the situation, and the interceptor body has to make a back turn after launch for the purpose. The operational flow of our engagement strategy is illustrated in Fig. 2, where the notation \( \Omega \) is defined as the defensible volume covered by GVLG.

In reference [11], the fuzzy logic based guidance law in midcourse, shaping and terminal phases have been developed. Our focus here is particularly on development of the vertical guidance law.

A. VERTICAL GUIDANCE STRATEGY

There are two actions to be implemented during the vertical guidance phase. First, the interceptor has to roll to an orientation toward the oncoming target so that the pitch plane of the interceptor’s body coordinate are placed approximately in the same vertical plane to simplify the maneuver and reduce the required lateral acceleration in the horizontal plane. Second, the interceptor body is forced to incline and commence the course of engagement while it reaches a favorable altitude.

B. GVLG

The next step is to drive the interceptor to trace a desired flight path toward the target, see Fig. 3(a). This is fulfilled by exerting a negative pitch acceleration to change its attitude. The strategy is to choose the pitch flight path error angle \( \gamma - \gamma_d \), which \( \gamma_d \) denoting the desired flight path angle, and its change rate \( \dot{\gamma} \) as the antecedent variables of a fuzzy inference system \( f_i(\cdot, \cdot) \) to infer the guidance command \( \alpha_i \).

The desired pitch angle at this stage is defined by

\[ \gamma_d = \tan^{-1}\left(\frac{h_{\beta} - h_{\beta_0}}{x_f - x_{\beta_0}}\right) \]

where \( (x_{\beta_0}, h_{\beta_0}) \) are the interceptor’s instantaneous coordinates in the pitch plane when the inclination starts, and

\[ x_f = x_i + v_n \hat{t}, \quad h_f = h_i + v_{n}\gamma \]

with \( \hat{t} \) being the time-to-go to the preset lock-on point given by

\[ \hat{t} = -\text{PPIP} / \|\text{PPIP}\| \]

in which the predicted lock-on range \( \text{PPIP} \) is given by

\[ \text{PPIP} = \frac{v_{\text{avg}}}{v_{\text{avg}} - v_{\text{avg}} + R_{\text{lock}}} \]

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Fig. 1. Definitions of \( \alpha \) and \( \phi \)

Fig. 2. Operational flow of the engagement strategy
where \( R_{\text{soc}} = \sqrt{R_{\text{soc}}^2 + R_{\text{soc}}^2} \), \( v_m = \sqrt{v_m^2 + v_m^2} \), and \( R_{\text{soc}} \) is the seeker lock-on range which is assumed to be constant.

\begin{equation}
\gamma = \theta - \psi \sigma = -\gamma \gamma \pi
\end{equation}

Fig. 3. Engagement scenario for the vertical launch interceptor: (a) without BT, (b) with BT.

C. VLBG

When the target has already come close to the top of the launcher, raising the interceptor body must be fulfilled; see Fig. 3(b). The desired interceptor flight trajectory for the vertical plane is illustrated in Fig. 4(a). The BT point is denoted by \( M \) with the turning angle \( \gamma_1 = \gamma_1 \), where \( \gamma_1 \) is the target’s flight path angle in the pitch plane and \( M \) is the desired height of the turning point. We denote PIP as the predicted interception point and let

\begin{equation}
P_{\text{IP}} = P_{\text{IP}} - M
\end{equation}

Therefore

\begin{equation}
bM = \frac{P_{\text{IP}}}{\tan \gamma_1} - P_{\text{IP}}
\end{equation}

where \( P_{\text{IP}} \) and \( P_{\text{IP}} \) are the distances between the launcher and the target in the \( X \) and \( H \) axes with respect to PIP, respectively. We take the range \( LOP_{\text{M}} \) to be

\begin{equation}
LOP_{\text{M}} = bM \tan \gamma_1
\end{equation}

Then, the desired flight path from \( M \) to the counter parallel flight path is

\begin{equation}
FM = LOP_{\text{M}} \cos \gamma_1
\end{equation}

The coordinates of the point \( F \) in the pitch plane are given by \( (FM \sin \gamma_1, FM \cos \gamma_1 + Mz) \). The entire operation consists of two parts: Phase I - when the interceptor reaches the specified turning point \( M \) it is ready to make a turn with \( \gamma_1 \) set to be \( \gamma_1 + 0.5\pi \); Phase II - \( \gamma_2 \) is changed to \( \gamma_2 \) when the interceptor attains the midpoint, denoted by \( N = (N_x, N_y, N_z) \), of the flight path \( FM \). Similarly, we denote the midpoint of \( LOP_{\text{F}} \) by \( Q = (Q_x, Q_y, Q_z) \).

For the horizontal plane illustrated in Fig. 4(b), when the interceptor attains the BT point, it is required to make a turn and the desired flight path angle is set to be \( \gamma_2 + 0.5\pi \) before it attains \( LOP_{\text{F}} \) with \( \gamma_2 \) denoting the target’s flight path angle in the horizontal plane.

To achieve an exact orientation in the pitch plane, let us consider the relative motion between the interceptor and target. Clearly, there are

\begin{equation}
\dot{R}_{\text{match}} = -v_m \cos \sigma \gamma
\end{equation}

\begin{equation}
R_{\text{min}} \dot{\theta} = -v_m \sin \sigma \gamma
\end{equation}

Differentiating Eq. (19) with respect to time and combining these equations yields

\begin{equation}
\ddot{\theta}_{\gamma} = \left( \frac{\dot{v}_m - 2\dot{R}_{\text{match}}}{v_m} \right) \dot{\theta} + \frac{R_{\text{match}}}{R_{\text{match}}} \gamma
\end{equation}

Without loss of generality, assume \( \dot{v}_m/v_m \approx 0 \). Then

\begin{equation}
\ddot{\theta} = (2\dot{\theta} - \gamma)/(t_{\text{pop}}), \text{where } t_{\text{pop}} = -R_{\text{match}}/\dot{R}_{\text{match}}
\end{equation}

Consider minimization of the following cost function

\begin{equation}
J = \int_0^{t_{\text{pop}}} \gamma^2(t)dt
\end{equation}

Subject to Eq. (21) and \( \dot{\theta}(t) = \gamma \), \( \dot{\theta}(t) = 0 \). One can obtain the optimal solution given by

\begin{equation}
\gamma = 2 \sqrt{\gamma_2^2 - \gamma_1^2 + 4\dot{\theta}}
\end{equation}

On the basis of this result, the guidance law is generalized in the following form:

\begin{equation}
a_n = \frac{v_m \gamma}{t_{\text{pop}}} = -N_1 \frac{v_m}{t_{\text{pop}}} (\gamma - \theta) + N_2 \gamma \dot{\theta}
\end{equation}

In which \( N_1 \) acts as the guidance gain with respect to the heading error \( \gamma - \theta \), \( N_2 \) plays the similar role as the conventional proportional navigation guidance gain.

To design the midcourse guidance law in which the interceptor could reach a near head-on geometry before entering the terminal phase, we define the range to the preset lock-on point as

\begin{equation}
R_{\text{p}} = R + R_{\text{soc}}
\end{equation}

where \( R = \sqrt{R_{\text{soc}}^2 + R_{\text{soc}}^2} \). The estimated time-to-go to the preset lock-on point is

\begin{equation}
t_{\text{pop}} = \frac{R_{\text{p}}}{R_{\text{soc}}}, \text{ where } R_{\text{p}} = \frac{R_{\text{p}}}{R_{\text{soc}}}
\end{equation}

where \( v_{rx} = \sqrt{v_{mx}^2 - v_{mx}^2} \), \( v_{ry} = \sqrt{v_{my}^2 - v_{my}^2} \), \( v_{rh} = v_{mh} - v_{mh} \), \( v_{nx} = \sqrt{v_{nx}^2 + \gamma \cos \psi} \), \( v_{ny} = \sqrt{v_{ny}^2 + \gamma \cos \psi} \), \( v_{nz} = \sqrt{v_{nz}^2 + \gamma \sin \psi} \), and \( v_{nd} = \sqrt{v_{nd}^2 + \gamma \sin \psi} \). The desired flight-path angles on both planes are specified as

\begin{equation}
\gamma_d = \tan^{-1} \left( \frac{\dot{h}_{\gamma} - h_m}{x_m - x_m} \right), \text{ and } \psi_d = \tan^{-1} \left( \frac{y_{\gamma} - y_m}{x_m - x_m} \right)
\end{equation}
where \( x_f = x_i + v_x t \) and \( y_f = y_i + v_y t \), and \( h_f = h_i + v_h t \). The predicted LOS angle with respect to the lock-on point is given by

\[
\hat{\theta}_i = \tan^{-1}\left( \frac{\hat{h}_i - h_m}{\hat{x}_i - x_m} \right), \quad \hat{\theta}_h = \tan^{-1}\left( \frac{\hat{y}_i - y_m}{\hat{x}_i - x_m} \right)
\]

(26)

where \( \hat{x}_i = x_i + v_x \), \( \hat{y}_i = y_i + v_y \) and \( \hat{h}_i = h_i + v_h \) with

\[
\hat{i} = \frac{R_{\text{lock}}}{R_p} = \frac{R_{\text{lock}}}{R_p v_x + R_{\text{lock}} v_y + R_{\text{lock}} v_{\phi}}
\]

(27)

The predicted velocity error angles are defined by

\[
\hat{\gamma} = \gamma - \gamma_d, \quad \hat{\psi} = \psi - \psi_d
\]

(28)

and the corresponding heading error angles are defined as

\[
\sigma_v = \gamma - \hat{\theta}_i, \quad \sigma_h = \psi - \hat{\theta}_h
\]

(29)

### IV. FUZZY LOGIC GUIDANCE LAW DESIGN

#### A. FUZZY GUIDANCE LAW-VERTICAL LAUNCH WITHOUT BT

**Vertical roll** \( M_z = f_v(Z, \alpha)

The linguistic variables for the guidance law are \( Z \) and \( \alpha \), and the output variable is the desired height \( M_z \). Each linguistic variable is assumed to be characterized by three linguistic sets, see Fig. 5. Illustration of the ideal arrangement is displayed in Fig. 6 which is realized by 9 rules in Table 1. Finer guidance decisions are directly obtainable by expanding the rule base.

<table>
<thead>
<tr>
<th>( M_z )</th>
<th>N</th>
<th>R</th>
<th>F</th>
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<tbody>
<tr>
<td>Z</td>
<td>L</td>
<td>L</td>
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<tr>
<td>H</td>
<td>M</td>
<td>M</td>
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Fig. 5. MFs adopted in the vertical launch phase: (a) \( R \) (m), (b) \( Z \) (m), (c) \( M_z \) (m)

#### Fig. 6. Illustrations of the inferred altitude for the vertical guidance law

**Attitude change** \( \alpha_v = f_v(\gamma - \gamma_d, \dot{\gamma})

The input variables are the flight path error angle \( \gamma - \gamma_d \) and its change rate \( \dot{\gamma} \). The output variable is \( \alpha_v \). Each linguistic variable takes 5 linguistic sets, see Fig. 7. The fuzzy rule base is given in Table 2. The design criteria can be summarized as follows:

Group 1: Both of \( \gamma - \gamma_d \) and \( \dot{\gamma} \) are very small or close to zero. This means that the current LOS angle is close to \( \gamma_d \). Thus, the amount of control action is small and intended to slightly correct the deviation.

Group 2: \( \gamma - \gamma_d \) and \( \dot{\gamma} \) are positive. The flight-path angle is larger than \( \gamma_d \) and it is flying downward. Control action is thus designed to lift the interceptor.

Group 3: \( \gamma - \gamma_d \) is negative and \( \dot{\gamma} \) is positive. This means that the interceptor’s flight-path angle is less than \( \gamma_d \) and it is flying downward. Control action is thus designed to further lower the interceptor’s attitude to speed up the convergence of \( \gamma - \gamma_d \).

Groups 4 and 5: They are opposite to Groups 3 and 2, respectively.

<table>
<thead>
<tr>
<th>( \alpha_v )</th>
<th>( \gamma )</th>
<th>( \dot{\gamma} )</th>
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<tr>
<td>LN</td>
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<td>LP</td>
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Fig. 7. Illustrations of the inferred attitude for the vertical guidance law

### Table 1. Fuzzy vertical guidance rule base-Cases I & II

<table>
<thead>
<tr>
<th>( M_z )</th>
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Table 2. Fuzzy vertical guidance rule base
and $\sigma_\delta = \delta$; the former is thus weighted heavier.

For briefness, the details are omitted. The inferred guidance commands defined above are defuzzified before sending to the autopilot. The crisp control use the center average defuzzifier to ensure smoothness of the resulting guidance commands.

**V. RESULTS AND ANALYSES**

Parameter settings for the target and the interceptor in [11] were adopted. A Poisson evasive model was adopted to emulate the random target maneuver with the magnitudes of $a_\theta (t)$ and $a_\delta (t)$ being 5 g. Time constant of the first-order shaping filter realized the model was 1 sec. To characterize the defensible volume, the acceptable MD for each scenario was 10 m. The MD for each scenario depicted later is the mean value of a total of 10 Monte Carlo runs.

A. VERTICAL LAUNCH WITHOUT BT

The guided missile is required to intercept the target with higher terminal speed. The resulting defensible volume is shown in Fig. 9 which shrinks with the increasing altitude. This is consistent to our previous study for the slanted launch case, which showed that the defensible volume would be larger when the launcher’s slanted angle is about 45 degrees in [10].

The guidance law switches to the terminal guidance phase after BT is completed. That is, the interceptor has already attained the extended line of abF in Fig. 4(a) with the flight path angle $\gamma \approx \gamma_t$. For briefness, the details are omitted.

B. FUZZY GUIDANCE LAW-VERTICAL LAUNCH WITH BT

Three actions have to be implemented during the vertical guidance phase, i.e. vertical roll, BT and twist. The first fuzzy rule base is to determine an appropriate back turning height $M_z$ with the input variables $Z_i$ and $R_i$.

The corresponding MFs are defined in Fig. 8 and the guidance rules have been depicted in Table 1. The guidance command for changing the interceptor’s attitude is generated by Eq. (22) using the heading error angle $\gamma_s - \theta$, and $\delta$. The corresponding MFs are defined in Fig. 8 and the guidance rules have been depicted in Table 1. The guidance command for changing the interceptor’s attitude is generated by Eq. (22) using the heading error angle $\gamma_s - \theta$, and $\delta$.

![Fig. 7. MFs for the BT in the vertical launch mode: (a) $\gamma - \gamma_s$ (deg), (b) $\dot{\gamma}$ (deg/s), (c) $\alpha_\beta$ (deg)](image)

![Fig. 8. MFs for $M_z$ in the vertical launch case with BT: (a) $R$ (m), (b) $Z$ (m), (c) $M_z$ (m).](image)

![Fig. 9. Defensible volumes for the vertical launch case in: (a) fourth quadrant, (b) 3D space](image)
A. FINER GUIDANCE COMMANDS

Results for the target with the reentry coordinates (16600, 16730, 38500) (m) are demonstrated. When the interceptor attained the turning point in Fig. 4 the remaining relative range between interceptor and target was less than 15 km which wasn’t long enough to build up its speed for an effective interception. By applying the proposed guidance law, improvement of the defense capability is illustrated in Fig. 11. The engagement trajectories are displayed in Fig. 12.

VI. CONCLUSIONS

An integrated fuzzy logic-based guidance scheme is developed to guide the vertical launch interceptor to intercept high-speed reentry targets. The engagement strategy includes general vertical launch and vertical launch with back turn, which are shown to be appropriate to deal with the cases of longer and shorter engagement ranges. The guidance law at each engagement phase is realized by a fuzzy logic inference system to incorporate finer guidance commands.

B. VERTICAL LAUNCH WITH BT

Fig. 10. Related response profiles correspond to the target with the reentry coordinates (29000, 28500, 44300) (m); (a)-(b) velocity error angle and heading error angle of the vertical plane; (c)-(d) velocity error angle and heading error angle of the horizontal plane

Fig. 11. Extra defensible volume contributed by the guidance strategy of vertical launch with BT in the fourth quadrant.

Fig. 12. Engagement trajectories corresponding to the target with the reentry coordinates (16600, 16730, 38500) (m); (a) relative distance between interceptor and target in the X-H plane and (b) X-Y plane

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