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Command governor for impact-angle guidance to fast targets under field-of-view constraint

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ABSTRACT

This paper introduces a command governor for two-phase impact-angle control guidance schemes applicable to air-to-air engagements. Although two-phase guidance is effective in surface-to-surface interception, it shows limitations for aerial targets with speeds similar to or greater than those of the interceptor. To improve the switching guidance scheme for anti-air missiles while complying with the seeker field-of-view constraint and terminal impact-angle requirements, we introduce a command governor that generates a look-angle command to track during the first guidance phase. The proposed command governor integrates a correction policy based on the solution characteristics in the first phase and prediction-based correction in the second phase. Hence, interception of fast aerial targets with a specified impact angle is achieved by incorporating the proposed command governor into the two-phase guidance scheme. An analysis of the region of feasible initial conditions ensures the capturability of the guidance law, and numerical simulations illustrate its effectiveness for interception at specified impact angles.

1. Introduction

Strap-down seekers for guided missiles are being increasingly explored. Their main benefits include their simple mechanism, light weight, and cost efficiency. Several missile systems employ strap-down seekers as sensor systems [1,2]. In response to the increased use of strap-down seekers in missiles, extensive research on guidance law design has been conducted by accommodating the effects of strap-down seekers, such as the parasitic effect or field-of-view (FOV) limit.

To intercept a fast target, the FOV limit should be considered in a sophisticated guidance scheme. Compared with ground targets, air threats usually move faster, and engagement generally lasts a few seconds. To address these challenges, an advanced seeker must accurately detect and track fast targets over long distances to ensure a sufficient detection time. However, the guaranteed detection distance has a tradeoff with the FOV width because seeking long detection ranges drastically reduces the FOV. Consequently, guidance design to intercept fast-moving targets should be carefully designed while consistently detecting the target using a narrow-FOV seeker.

Missile guidance laws have been developed to address the FOV limit of the seeker considering various objectives, such as impact time control

[3–8], impact-angle control (IAC) [9–18], and simultaneous impact-angle and time control [19–21]. To address FOV constraints in IAC guidance, common approaches involve switching strategies [5,10,22–29]. Such strategies use two-phase guidance laws with a logic switch between the phases. For instance, pure proportional navigation guidance (PPNG) is employed in the homing phase to attain the desired interception conditions [5,10]. However, PPNG alone cannot accommodate additional constraints on the impact angle and look-angle limits. Hence, pursuit guidance, or look-angle control (LAC) guidance, as a form of constrained maneuvering, is used in the first phase to ensure that the look angle remains within the FOV limit [23,30]. This switching guidance scheme has demonstrated advantages in intercepting surface targets with the largest impact-angle set [22,28]. Moreover, recent advancements in FOV-constrained IAC guidance techniques have broadened their scope to intercept slow targets [23,24], analyze capture regions [25,26], and address maneuvering targets [31–33] under wide FOV and speed advantage conditions, being also suitable for ground-target interception.

Despite its effectiveness for surface targets, the switching guidance scheme may reveal limitations for aerial targets, particularly in air-to-air engagement, in which the engagement time is drastically shortened.

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Abrupt adjustments of the flight path within a short time often lead to interception failure [26]. Moreover, interceptors frequently lack speed superiority over the target, requiring a narrow FOV and exacerbating engagement complexities. In long-distance air-to-air engagements, missiles with narrow FOVs ensure a sufficient detection range, but the maneuverability and collision geometry are restricted, thereby reducing the achievable impact angles. To ensure successful target interception and switching, guidance schemes must adapt to constraints imposed by the interceptor limited maneuverability and seeker FOV limit. Although the interception of moving targets with FOV constraints and target maneuverability has been widely investigated, existing methods do not fully integrate the necessary considerations, which diminishes their effectiveness in air-to-air engagements.

In this study, we propose a command governor for generating look-angle commands to control the impact angle for fast targets. The command governor is an add-on scheme that imposes state and control constraints by modifying the reference command into a well-designed closed-loop system [34–36]. The proposed method can be incorporated into existing switching guidance schemes, such as those proposed in [22,23,25–28], for successful interception with the desired impact angle. Because the capturability of a switching-based guidance law depends on the maneuver performed in the first phase, the proposed governor aims to provide a suitable command to the guidance system during that phase. The proposed governor comprises two steps. In the first step, a command correction policy is established based on the solution characteristics that depend on the engagement type. In the second step, a prediction-based correction is applied according to the system limitations, such as restricted acceleration and FOV. To evaluate the performance improvement provided by the proposed scheme, we characterized the region of feasible initial conditions for the capturability of the guidance law and conducted numerical simulations. Simulation results demonstrated the effectiveness of the proposed command governor for achieving successful interception of fast targets with the desired impact angle.

This study yields two primary contributions. First, the proposed command governor substantially enhances the performance of conventional switching guidance schemes, enabling the successful interception of fast targets in air-to-air engagements. By integrating the proposed reference command into well-established switching guidance schemes, our add-on approach enables effective impact-angle interception without requiring major modifications to the guidance loop. Second, the proposed command governor handles a narrow FOV and speed inferiority of the interceptor, which have been scarcely studied. A capturability analysis demonstrates that the proposed add-on concept expands the capture region. Overall, this study provides insights into enhancing the adaptability and effectiveness of switching-based guidance schemes for air-to-air engagements.

2. Preliminaries

The engagement kinematics are described in Sec. 2.1, and the switching guidance scheme is presented in Sec. 2.2 as the baseline method in this study. Then, the problem is formally stated in Sec. 2.3 for designing a constant look-angle command for the first phase of the baseline method.

2.1. Engagement kinematics

In this study, an air-to-air engagement between a missile and target is considered. The missile and target move on an engagement plane, as shown in Fig. 1. The following assumptions are considered:

Assumption 1. The target is non-maneuvering; that is, $\dot{\gamma}_T = 0$.

Assumption 2. The FOV is sufficiently narrow to confine the collision geometry such that $\sin \sigma_{\text{lim}} < \eta$, where $\eta = V_T/V_m$ is the speed ratio.

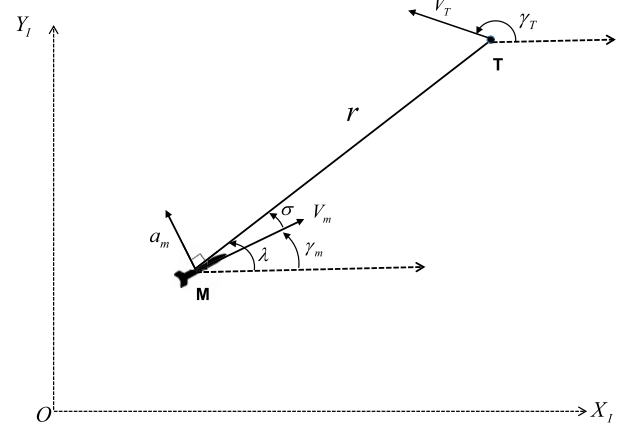


Fig. 1. Engagement Kinematics.

The assumptions are adequate for air-to-air engagements. Assumption 1 is reasonable to represent high-speed air-to-air engagements that last only a few seconds at most. The target primarily travels along its axial direction in such a short amount of time. Assumption 2 dictates the narrowness of the FOV limit with respect to the speed ratio. This narrowness not only restricts the maneuverability of the interceptor but also confines the collision geometry because $\sin \sigma_{\text{lim}} < \eta$ implies a confined collision condition. Most studies have neglected such conditions because the interceptor speed is superior to that of the target. On the other hand, aerial target engagement requires a very narrow FOV limit to expand the detection range.

In this study, we focus on impact-angle-constrained interception. Here, the impact angle is defined as the terminal flight-path angle of the vehicle, which can be written as

$$\gamma_f = \gamma_m(t_f) \quad (1)$$

For precise interception with the desired impact angle, information regarding target speed V_T and flight path angle γ_T must be provided, which can be estimated using a target-tracking filter. We assume that accurate target information is available. The effect of inaccurate target information on the performance of the proposed guidance loop is analyzed using simulations that incorporate a target-tracking filter. The width of the FOV limit is defined by the speed ratio [25]. When the target is faster than the missile, interception must be achieved using a head-on (HO) geometry. Assumption 2 is satisfied when the speed ratio exceeds unity. The engagement kinematics can be represented as follows:

$$\dot{r} = V_T \cos(\gamma_T - \lambda) - V_m \cos \sigma \quad (2a)$$

$$\dot{\lambda} = \frac{V_T}{r} \sin(\gamma_T - \lambda) + \frac{V_m}{r} \sin \sigma \quad (2b)$$

$$\dot{\sigma} = \frac{V_T}{r} \sin(\gamma_T - \lambda) + \frac{V_m}{r} \sin \sigma - \frac{a_m}{V_m} \quad (2c)$$

$$\dot{\gamma}_m = \frac{a_m}{V_m} \quad (2d)$$

where r is the distance between the missile and target, λ is the line-of-sight (LOS) angle, σ is the missile look angle, (V_m, γ_m) is the pair of speed and flight path angle of the missile, respectively, (V_T, γ_T) is the pair of speed and flight-path angle of the target, respectively, and a_m is the normal acceleration of the missile. Assuming a small attack angle, the look angle is defined as

$$\sigma = \lambda - \gamma_m \quad (3)$$

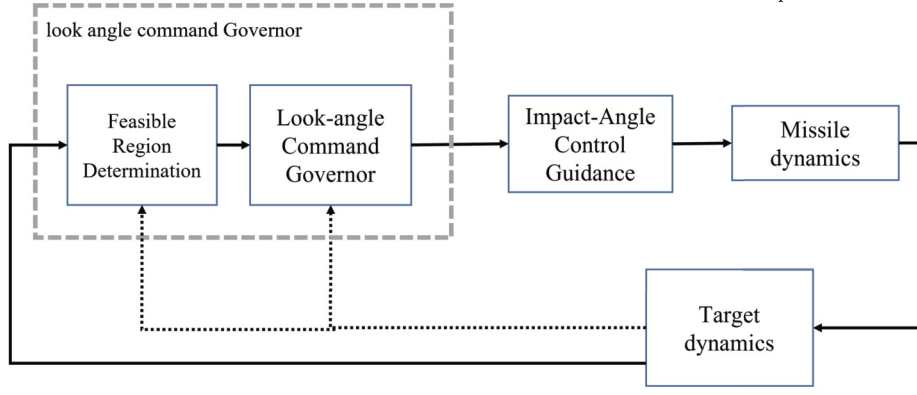


Fig. 2. Schematic of Proposed Guidance Law.

2.2. Switching guidance scheme for FOV and impact-angle constraints

This section presents the overview for switching guidance, illustrated in Fig. 2. The scheme uses composite guidance laws with switching logic [22,23,27,28]. This scheme is widely used in FOV-constrained guidance and is beneficial because of its simple structure and effectiveness in achieving interception with the desired impact angle and FOV constraint. The guidance commands for each phase are described in the following sections.

2.2.1. Guidance law for first phase

In the first guidance phase, the switching guidance scheme implements LAC for the missile to reach the desired initial configuration for the second phase. Let (σ_s, λ_s) be a pair of parameters corresponding to the switching configuration. To ensure that the look angle remains within the FOV range and a bounded guidance command, the LAC guidance command takes the following form:

$$a_{cmd,1} = V_m [\dot{\lambda} + k|\sigma - \sigma_c|^p \text{sign}(\sigma - \sigma_c)] \quad (4)$$

where σ_c denotes the look-angle command to be designed and $k > 0$ and $0 < p < 1$ are design parameters. The look-angle error is defined as $e = \sigma - \sigma_c$. Substituting Eq. (2c) into Eq. (4) gives the error dynamics as follows:

$$\dot{e} = -k|e|^p \text{sign}(e) \quad (5)$$

The error dynamics considered in this study exhibits a finite-time convergence property (Theorem 2 in [37]). The detailed proof is provided in Appendix A.

2.2.2. Guidance law for second phase

In the second guidance phase, PPNG is used for target interception at a given impact angle. PPNG drives the missile through the collision course by maintaining a flight direction proportional to the LOS rate. The PPNG command is expressed as

$$a_{cmd,2} = NV_m \dot{\lambda} \quad (6)$$

where N is a constant navigation gain that should be greater than 2 to decrease the LOS rate consistently, as discussed in [38,39]. For interception at a specified impact angle, the desired collision course in terms of the LOS angle can be obtained considering the engagement geometry as [26]

$$\lambda_f = \tan^{-1} \left(\frac{\sin \gamma_f - \eta \sin \gamma_T}{\cos \gamma_f - \eta \cos \gamma_T} \right) \quad (7)$$

By substituting Eq. (6) into Eq. (2d) and integrating by parts, we obtain

$$\gamma_f - \gamma_s = N(\lambda_f - \lambda_s) \quad (8)$$

The initial LOS angle required to reach the desired collision course given by Eq. (7) can be obtained by considering the relation between the angles, as given by Eq. (3).

$$\lambda_s = \left(\frac{N}{N-1} \right) \left(\lambda_f - \frac{\gamma_f + \sigma_0}{N} \right) \quad (9)$$

Finally, the switching guidance law is expressed in a unified form as follows:

$$a_{cmd} = \begin{cases} V_m [\dot{\lambda} + k|\sigma - \sigma_c|^p \text{sign}(\sigma - \sigma_c)] & \left| \lambda - \lambda_f \right| > \left| \lambda_s - \lambda_f \right| \\ NV_m \dot{\lambda} & \left| \lambda - \lambda_f \right| \leq \left| \lambda_s - \lambda_f \right| \end{cases} \quad (10)$$

By appropriately selecting navigation gain N , the LOS angle converges monotonically from λ_s to λ_f . If the initial pair (σ_0, λ_0) does not satisfy Eq. (9), a turning maneuver should be performed before switching to PPNG. Additionally, the lock-on condition is automatically satisfied when σ_0 and σ_f are within the bounds of its FOV range.

2.3. Problem statement

Let $\Sigma := [-\sigma_{\lim}, \sigma_{\lim}]$ denote the invariant set of admissible look angles. Recall that the desired impact angle, γ_f , is defined as the terminal flight path angle, $\gamma_f = \gamma_m(t_f)$ as introduced in Eq. (1). For the IAC guidance problem considering the FOV limit, homing guidance is intended to intercept the approaching or retracting target while satisfying the following conditions:

Condition 1 (Consistency of lock-on condition). The look angle must remain in invariant set, i.e., $\sigma \in \Sigma, \forall t \in [t_0, t_f]$.

Condition 2 (Feasible guidance command under missile maneuverability). The guidance command should be bounded by the maximum allowable acceleration limit, that is, $|a_{cmd}| \leq a_{\lim}$.

Condition 3 (Allowable miss distance for hit-to-kill interception). The distance between the missile and target at the interception instant must be less than the allowable value, that is, $r(t_f) < r_{miss}$.

Condition 4 (Interception with desired impact angle). The error in the impact angle must be bounded by an acceptable range, that is, $|\gamma_f - \gamma(t_f)| < \epsilon$.

Considering the switching guidance scheme, conditions 3 and 4 are automatically satisfied if guidance parameters such as N of PPNG in the second phase are properly chosen and the second phase follows from a favorable initial phase. In addition, the state invariance described in condition 1 is ensured by a proper choice of the desired error dynamics and corresponding command. The ideal response for the chosen error dynamics does not exhibit any overshooting behavior as it describes a first-order dynamics in e . If any imperfection makes the true evolution

of error deviate from the ideal response but $|e|$ is bounded by a non-zero constant, we may take more conservative limits for σ_c so that σ stays within the physical limits. In this study, we adopt the switching guidance scheme given by Eq. (10) by selecting error dynamics that exhibits finite-time convergence with an overdamped response. Therefore, the design objective of the proposed command governor is to ensure that Conditions 1 and 2 are satisfied in the initial phase. The design objective can be stated as follows.

Problem 1 (Design objective of command governor). Consider the equations of motion given in Eq. (2). Under the switching guidance law in Eq. (10), the objective of the command governor is to find a feasible look-angle command, σ_c , such that the switching guidance law holds for the following conditions:

$$\sigma_c \in \Sigma = [-\sigma_{\text{lim}}, \sigma_{\text{lim}}], \forall t \in [t_0, t_f] \quad (11)$$

$$|a_{\text{cmd}}(\lambda_s(\sigma_c))| \leq a_{\text{lim}}, \quad \text{at } \lambda = \lambda_s(\sigma_c) \quad (12)$$

3. Proposed look-angle command governor

This section presents the command generation for the command governor concept [36] to improve LAC in the first phase. The look-angle command, σ_c , is generated to determine switching instance λ_s based on Eq. (9). To this end, we propose a two-stage command-generation method.

3.1. Feasible region for stable guidance transition

The initial stage of generating the look-angle command involves determining the update direction for σ_c based on a favorable engagement geometry at the switching instant and guided trajectory properties. Assuming that σ_c is specified, a proper configuration allows the missile to reach the switching condition while maintaining a constant look angle. The LAC guidance system has two limit points in the tail-chase (TC) and HO geometries, denoted by λ_{TC}^* and λ_{HO}^* , respectively, which can be expressed in terms of σ_c using Eqs. (3), (7), and (9).

$$\lambda_{TC}^*(\sigma_c) = \gamma_T + \sin^{-1} \left(\frac{V_m}{V_T} \sin \sigma_c \right) \quad (13)$$

$$\lambda_{HO}^*(\sigma_c) = \gamma_T + \pi - \sin^{-1} \left(\frac{V_m}{V_T} \sin \sigma_c \right) \quad (14)$$

where

$$\lambda_s(\sigma_c) = \left(\frac{N}{N-1} \right) \left(\tan^{-1} \left(\frac{\sin \gamma_f - \eta \sin \gamma_T}{\cos \gamma_f - \eta \cos \gamma_T} \right) - \frac{\gamma_f}{N} \right) - \frac{\sigma_c}{N-1} \quad (15)$$

The behavior of the closed-loop system near the limit point can fluctuate. Proposition 1 describes the characteristics of a closed-loop system according to the engagement geometry.

Proposition 1 (Characteristics of LAC guidance in TC/HO engagement). Suppose that σ is kept constant as σ_c in a finite time. For TC engagement, that is, $\Lambda_{TC} = \{\gamma_T - \pi/2 \leq \lambda \leq \gamma_T + \pi/2\}$, the LOS angle monotonically converges to λ_{TC}^* . By contrast, for HO engagement, that is, $\Lambda_{HO} = \{\gamma_T + \pi/2 \leq \lambda \leq \gamma_T + 3\pi/2\}$, the LOS angle diverges from λ_{HO}^* .

Proof. See Appendix B. $\square$

Proposition 1 provides a stable switching configuration that can be used to obtain the LOS angle at switching instant λ_s . This can be achieved by integrating the LOS rate from the current LOS angle as follows:

$$\lambda_s = \lambda + \int_t^{t_s} \dot{\lambda} d\tau \quad (16)$$

Table 1

Divided Sectors Resulting from Three-tuples in TC Engagement ($\lambda, \lambda_s, \lambda_{TC}^*$).

Sector	Domain	Update direction of σ_c
$S_{TC,1}$	$\lambda_s < \lambda < \lambda_{TC}^*$	Decrease σ_c
$S_{TC,2}$	$\lambda_s < \lambda_{TC}^* < \lambda$	Decrease σ_c
$S_{TC,3}$	$\lambda_{TC}^* < \lambda_s < \lambda$	No update
$S_{TC,4}$	$\lambda_{TC}^* < \lambda < \lambda_s$	Increase σ_c
$S_{TC,5}$	$\lambda < \lambda_{TC}^* < \lambda_s$	Increase σ_c
$S_{TC,6}$	$\lambda < \lambda_s < \lambda_{TC}^*$	No update

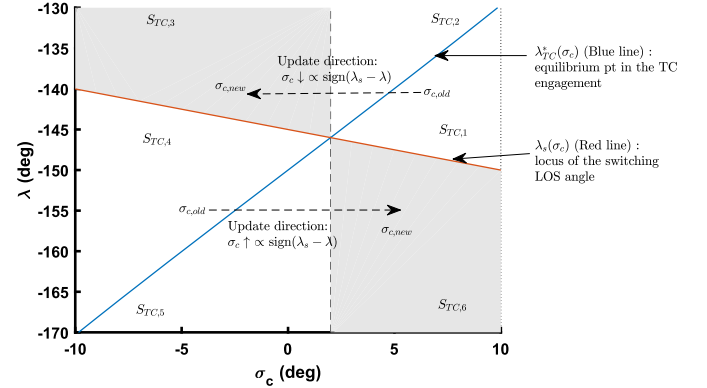


Fig. 3. Feasible Region for Stable Switching Geometry and Update Direction for Look-Angle Command in TC Engagement. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

In the TC geometry, the LOS angle monotonically converges to attractive limit point λ_{TC}^* , where $t_s > t$ is the switching time. The LOS rate has the same sign as the deviation from the current LOS to the limit point.

$$\text{sign}(\dot{\lambda}) = \text{sign}(\lambda_{TC}^* - \lambda), \quad \lambda \in \Lambda_{TC} \quad (17)$$

Given that $\dot{\lambda}$ is continuous and nonzero, we can relate the LOS angle and its integration to $\int_t^{t_s} \dot{\lambda} d\tau > 0$. Using Eqs. (17) and (16), λ_s can be expressed in terms of the limit point and current LOS angle as follows:

$$\begin{aligned} \lambda_s &= \lambda + \int_t^{t_s} \dot{\lambda} d\tau = \lambda + \kappa(\lambda_{TC}^* - \lambda) \\ &= \kappa\lambda_{TC}^* + (1 - \kappa)\lambda \end{aligned} \quad (18)$$

where $\kappa \in [0, 1]$ is the weight between λ and λ_{TC}^* . Eq. (18) indicates that λ_s is located between the limit point and current LOS angle. Switching the guidance phase is guaranteed if the relative geometry is maintained. Alternatively, Eq. (18) can be expressed as

$$(\lambda - \lambda_s)(\lambda_{TC}^* - \lambda_s) \leq 0 \quad (19)$$

The desired switching geometry can be represented by a three-tuple, $(\lambda, \lambda_s, \lambda_{TC}^*)$, as illustrated in Fig. 3. In the $\sigma - \lambda$ space, this tuple determines the six sectors defined in Table 1. The desired switching geometries are given by

$$\begin{aligned} \Lambda_{0,TC} &= S_{TC,3}(\sigma_c) \cup S_{TC,6}(\sigma_c) \\ &= \{ \lambda : \lambda \leq \lambda_s \leq \lambda_{TC}^* \text{ or } \lambda_{TC}^* \leq \lambda_s \leq \lambda \} \end{aligned} \quad (20)$$

If the three-tuple does not satisfy the desired switching geometries expressed in Eq. (20), the order of the tuples should be rearranged by modifying the look-angle command.

Table 1 summarizes the desired update directions of σ_c for the different sectors. When $\lambda > \lambda_s$ (sectors $S_{TC,1}$ and $S_{TC,2}$), the tuple order can be rearranged as $\lambda_{TC}^* < \lambda_s < \lambda$ by reducing the value of σ_c . The red line in Fig. 3 represents $\lambda_s(\sigma_c)$, and the vertical dashed line represents $\sigma = \sigma_f$. These lines form the boundaries of favorable sectors. Considering the

feasible region with the corresponding boundary, it is reasonable to set look-angle command σ_c as limit σ_f because it forms the feasible region and allows for impact-angle completion by LAC guidance.

$$\sigma_{c,1} = \sigma_f \quad \text{if } \gamma_f \in \Lambda_{TC} \quad (21)$$

Similarly, the desired location of the switching LOS angle in the HO geometry can be determined. Table 2 summarizes the desired update directions of σ_c for the different sectors in the HO geometry, and Fig. 4 illustrates the update directions of σ_c . Using the divergent behavior from the unstable limit point, λ_{HO}^* , the direction of the LOS rate can be expressed in terms of the current LOS angle and limit point as

$$\text{sign}(\dot{\lambda}) = -\text{sign}(\lambda_{HO}^* - \lambda), \quad \lambda \in \Lambda_{HO} \quad (22)$$

According to the closed-loop characteristics, the appropriate geometry for the switching LOS angle can be expressed using Eqs. (22) and (16) as follows:

$$\begin{aligned} \lambda_s &= \lambda + \int_t^{t_s} \dot{\lambda} d\tau = \lambda - \kappa(\lambda_{HO}^* - \lambda) \\ &= -\kappa\lambda_{HO}^* + (1 + \kappa)\lambda \end{aligned} \quad (23)$$

Note from Eq. (23) that the location of λ_s corresponds to the externally divided point between the limit point and current LOS angle. Eq. (23) can be rewritten as

$$(\lambda - \lambda_s)(\lambda_{HO}^* - \lambda_s) > 0 \quad (24)$$

The desired switching geometry can be expressed in terms of tuple $(\lambda, \lambda_s, \lambda_{HO}^*)$ as

$$\Lambda_{0,HO} = S_{HO,3} \cup S_{HO,6} = \{\lambda_{HO}^* \leq \lambda \leq \lambda_s \quad \text{or} \quad \lambda_s \leq \lambda \leq \lambda_{HO}^*\} \quad (25)$$

Otherwise, the order of tuple $(\lambda, \lambda_s, \lambda_{HO}^*)$ can be corrected by changing the look-angle commands. Considering the feasible region, $\lambda_s(\sigma_c)$ and λ_{HO}^* constitute the boundaries of the favorable sectors. Similar to Eq. (21), look-angle command σ_c can be specified as

$$\sigma_{c,1} = \sigma_{HO}^* \quad \text{if } \gamma_f \in \Lambda_{HO} \quad (26)$$

where σ_{HO}^* represents the limit look angle for the current LOS angle.

Remark 1 (Infeasibility of TC engagement for faster target interception). Although the favorable switching geometry of Eq. (20) is achieved, a retracting target cannot be intercepted by PPNG when the target is much faster than the missile. Therefore, the correction algorithm for the TC geometry is only applicable to slower targets.

3.2. Prediction-based look-angle command correction

The proposed command governor performs prediction to correct the look-angle command and satisfy the constraints. Look-angle command σ_c can be selected in the feasible region and expressed in terms of its boundary points. According to the current LOS angle, the look-angle command can be corrected by considering the two boundaries, $\sigma_{c,2} = \lambda_s^{-1}(\sigma_c)$ and $\sigma_{c,1}$, assigned in the previous step. This correction is represented as follows:

$$\sigma_c = (1 - \kappa_1)\sigma_{c,1} + \kappa_1\sigma_{c,2} \quad (27)$$

where $\kappa_1 \in [0, 1]$ is the design parameter. When the look-angle command lies within feasible regions $\Lambda_{0,TC}$ and $\Lambda_{0,HO}$, the phase transition from LAC guidance to PPNG is achieved while satisfying the impact-angle constraint. Parameter κ_1 determines the look-angle command and transition timing during engagement. The guidance command must not violate the maneuver limits, particularly at the expected switching time. To ensure this condition, we incorporate prediction into command generation to examine this constraint. Suppose that look-angle command σ_c

Table 2

Divided Sectors Resulting from Three-tuples in HO Engagement $(\lambda, \lambda_s, \lambda_{HO}^*)$.

Sector	Domain	Update direction of σ_c
$S_{HO,1}$	$\lambda_{HO}^* < \lambda_s < \lambda$	σ_c Decrease
$S_{HO,2}$	$\lambda_s < \lambda_{HO}^* < \lambda$	σ_c Decrease
$S_{HO,3}$	$\lambda_s < \lambda < \lambda_{HO}^*$	No update
$S_{HO,4}$	$\lambda < \lambda_s < \lambda_{HO}^*$	σ_c Increase
$S_{HO,5}$	$\lambda < \lambda_{HO}^* < \lambda_s$	σ_c Increase
$S_{HO,6}$	$\lambda_{HO}^* < \lambda < \lambda_s$	No update

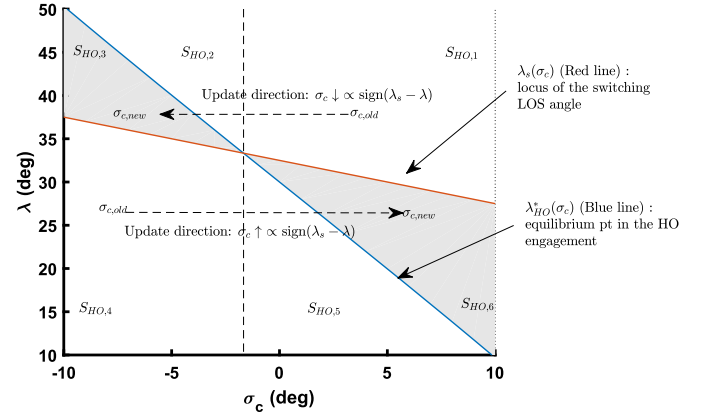


Fig. 4. Feasible Region for Stable Switching Geometry and Update Direction for Look-Angle Command in HO Engagement.

is chosen from the first step as $\sigma_{c,1}$ with $\kappa_1 = 0$. The trajectory obtained by LAC guidance can be considered equivalent to that obtained by the deviated pure pursuit guidance. The switching point can be predicted using a closed-form expression that depends on the given look-angle command σ_c .

$$\hat{r}_s = \Phi(\lambda_s, \lambda)r \quad (28)$$

where the transition function of deviated pure pursuit guidance $\Phi(\lambda_s, \lambda)$ is given by [26]

$$\begin{aligned} \Phi(\lambda_s, \lambda) &= \frac{\eta \sin(\gamma_T - \lambda) + \sin \sigma_c}{\eta \sin(\gamma_T - \lambda_s) + \sin \sigma_c} \\ &\times \exp \left\{ \frac{2 \cot \sigma_c}{\sqrt{1 - \zeta^2}} \left\{ \tan^{-1} \left(\frac{\tan \left(\frac{\gamma_T - \lambda_s}{2} \right) + \zeta}{\sqrt{1 - \zeta^2}} \right) \right. \right. \\ &\quad \left. \left. - \tan^{-1} \left(\frac{\tan \left(\frac{\gamma_T - \lambda}{2} \right) + \zeta}{\sqrt{1 - \zeta^2}} \right) \right\} \right\} \end{aligned} \quad (29)$$

with $\zeta = \eta / \sin \sigma_c$. In [26], the switching guidance command reaches an extreme value during the transition between guidance phases, which may lead to exceeding the maximum capability of the acceleration command based on the position at the switching time. Using Eq. (2), the LOS rate is proportional to $1/r$. Thus, the minimum distance, r_s , where the guidance command hits its limit, can be determined. By substituting $\lambda = \lambda_s$ and $\sigma = \sigma_c$, we obtain the switching criteria subject to constraints as follows.

Lemma 1 ([26]). Considering limited acceleration $-a_{\lim} \leq NV_M \dot{\lambda}_M \leq a_{\lim}$, the locus of the switching criterion is expressed as

$$(r_s, \lambda_s) \in \Omega_s = \{(r, \lambda) | \lambda = \lambda_s, r \geq r_s(\lambda_s)\} \quad (30)$$

where

$$r_s(\lambda_s; \sigma_c) = -\frac{NV_M V_T}{a_{\lim}} (\sin(\gamma_T - \lambda_s(\sigma_c)) + \eta \sin \sigma_c) \quad (31)$$

The maximum acceleration occurs in the switching instance [25]. Eq. (31) indicates the allowable range at the switching point in terms of r and λ_s . To achieve a maneuverable guidance command, the predicted value must exceed the lower bound of range r_s . Otherwise, the look-angle command must be further adjusted to achieve a guidance objective with limited maneuverability. When the current LOS angle is λ_s , the guidance loop transitions to the second phase. The desired look angle, $\sigma_{c,2}$, that corresponds to this condition for the current LOS angle can be obtained using Eq. (15) while considering the lock-on condition and substituting the current value of λ .

$$\sigma_{c,2} = \text{sat} \left(-(N-1)\lambda + N \left(\lambda_f - \frac{\gamma_f}{N} \right), \sigma_{lim} \right) \quad (32)$$

where $\text{sat}(a, a_{lim})$ is defined as

$$\text{sat}(a, a_{lim}) = \begin{cases} a_{lim} & a > a_{lim} \\ a & -a_{lim} \leq a \leq a_{lim} \\ -a_{lim} & a < -a_{lim} \end{cases} \quad (33)$$

The new look-angle command, $\sigma_{c,2}$, contributes to earlier switching compared with the previous look-angle command, σ_c . Even if look angle σ is equal to σ_c , the guidance loop continues the LAC maneuver until LOS angle λ reaches switching value $\lambda_s(\sigma_c)$. However, if the new command, $\sigma_{c,2}$, is followed, look-angle tracking automatically enables the guidance loop to transition to the second phase with $\lambda = \lambda_s(\sigma_{c,2})$ as the look angle converges to $\sigma_{c,2}$. Transitioning to the second phase earlier can be beneficial for interception because it allows the guidance loop to mitigate acceleration changes, which in turn helps avoid sudden and drastic maneuvers near the intercept. Therefore, design parameter κ_1 can be increased to reduce the acceleration at the expected switching instant. Owing to the transient response, command σ_c with $\kappa_1 \in [0, 1]$ confirmed at time t_1 may be outside the feasible region. This typically occurs when κ_1 is close to 1 in the early stage of the transient period. To prevent this problem, the feasibility condition is repeatedly checked, and the look-angle command is adjusted using new boundary points calculated from the current LOS angle.

Look-angle generation considering the sequential update logic is described in Algorithm 1.

4. Capture region analysis

We analyze the capture region of the proposed guidance law as in [26]. Under Assumption 2, the achievable impact set for a narrow FOV satisfies the following inequalities:

$$\sin \sigma_{lim} < \eta, \quad \tan \sigma_{lim} < \frac{\eta}{\sqrt{1-\eta^2}} \quad (34)$$

From Eq. (34), the collision geometry is confined by the FOV limit. The terminal flight path is confined as follows:

$$\Gamma_f = \{\gamma_f | \gamma_f \in [\gamma_{TC,min}^*, \gamma_{TC,max}^*] \cup [\gamma_{HO,min}^*, \gamma_{HO,max}^*]\} \quad (35)$$

where $\zeta_{lim} = \eta / \sin \sigma_{lim}$ and

$$\begin{aligned} \gamma_{TC,min}^* &= \gamma_T - \sin^{-1} \left(\frac{1}{\zeta_{lim}} \right) + \sigma_{lim}, \gamma_{TC,max}^* \\ &= \gamma_T + \sin^{-1} \left(\frac{1}{\zeta_{lim}} \right) - \sigma_{lim} \\ \gamma_{HO,min}^* &= \pi + \gamma_T - \sin^{-1} \left(\frac{1}{\zeta_{lim}} \right) - \sigma_{lim}, \gamma_{HO,max}^* \\ &= \pi + \gamma_T + \sin^{-1} \left(\frac{1}{\zeta_{lim}} \right) + \sigma_{lim} \end{aligned} \quad (36)$$

Suppose that the look-angle command is generated as described in Algorithm 1 for the impact angle selected in the confined collision geometry. The proposed method has the guidance structure used in [23]. Therefore, the boundaries of the capture region have a similar form. The

Algorithm 1: Look-Angle Command Generation.

Input : current missile and target information $\lambda, \gamma_f, V_T, V_m, \sigma, \gamma_T$
Return: look angle command σ_c , switching LOS angle λ_s
Initialize: $\sigma_c = \sigma_0$;
(1st step) Feasibility-based command generation;
 Calculate $\lambda_s, \lambda_{HO}^*$ and λ_{TC}^* using Eqs. (13)–(15);
 Check feasibility condition $\Lambda_{0,TC}$ and $\Lambda_{0,HO}$: Eqs. (20) and (25);
while $\lambda \notin \Lambda_{0,TC} \cup \Lambda_{0,HO}$ **do**
 if $\gamma_f \in \Lambda_{0,TC}$ **then**
 Calculate $\sigma_{c,1}$ using Eq. (21);
 else
 Calculate $\sigma_{c,1}$ using Eq. (26);
 end
 Update $\lambda_s, \lambda_{HO}^*$ and λ_{TC}^* by substitution of $\sigma_c \leftarrow \sigma_{c,1}$ into Eqs. (13)–(15);
 Update feasibility condition $\Lambda_{0,TC}$ and $\Lambda_{0,HO}$ using Eqs. (20) and (25);
end
 Determine command in the first step: $\sigma_c \leftarrow \sigma_{c,1}$;
(2nd step) Prediction-based command correction;
 Calculate boundary point $\sigma_{c,2}$ using Eq. (32);
Initialize: design parameters $\kappa_1 = 0, \epsilon \in (0, 1)$;
 Calculate the predicted switching distance $\hat{r}_s$ using λ_s and σ_c into Eq. (28);
while $(\hat{r}_s, \lambda_s) \in \Omega_s$ **do**
 $\kappa_1 \leftarrow \kappa_1 + \epsilon$;
 Calculate a temporary command $\sigma_{c,temp}$ using Eq. (27);
 Update λ_s and $\hat{r}_s$ by substitution of $\sigma_c \leftarrow \sigma_{c,temp}$ into Eqs. (15) and (28);
 Evaluate $r_s(\lambda_s)$ and Ω_s in Eq. (30);
end
 Confirm σ_c and λ_s ;
Return (σ_c, λ_s) ;

capture region of the switching guidance law comprises two boundaries, namely, i) the switching layer represented by Eq. (30) and ii) the deviated pure pursuit guidance solution from the minimum switching distance:

$$\text{Boundary 1} \quad (r, \lambda) : r \geq r_s, \quad \lambda = \lambda_s \quad (37a)$$

$$\text{Boundary 2} \quad (r, \lambda) : r = \Phi(\lambda, \lambda_s) r_s, \quad \Phi(\lambda, \lambda_s) > 1 \quad (37b)$$

The boundary trajectory in Eq. (37b) associated with σ_c is obtained using Eq. (29) by backward integration from the switching locus at the minimum distance, $r_s(\sigma_c)$. Considering the two boundaries, the capture region for look angle C_{γ_f, σ_c} can be obtained as follows:

$$C_{\gamma_f, \sigma_c} = \{(r_0, \lambda_0) | r_s(\lambda_s) \leq \Phi(\lambda_s, \lambda_0) r_0, \lambda_0 \in \Lambda_{0,TC}(\sigma_c) \cup \Lambda_{0,HO}(\sigma_c)\} \quad (38)$$

where $\Lambda_{0,TC}(\sigma_c)$ and $\Lambda_{0,HO}(\sigma_c)$ denote the initial domains of the TC and HO engagements defined in Eqs. (20) and (25), respectively. Considering the allowable range, $\sigma_c \in [\underline{\sigma}, \bar{\sigma}]$, the capture region of the proposed guidance law for impact angle C_{γ_f} is expressed as

$$C_{\gamma_f} = \bigcup_{\sigma_c \in [\underline{\sigma}, \bar{\sigma}]} C_{\gamma_f, \sigma_c} \quad (39)$$

Remark 2. Fig. 5 shows the capture region for exact HO and TC interception cases at different speed ratios. When the speed of the missile is higher than that of the target, the achievable initial positions are obtained (shaded area in Fig. 5(a)). The wide achievable range in the TC geometry indicates that interception is much easier than for HO engagement. Furthermore, the inclusion relation between C_{γ_f} and C_{IACCG, γ_f} in [26] shows that

$$C_{IACCG, \gamma_f} \subset C_{\gamma_f} \quad (40)$$

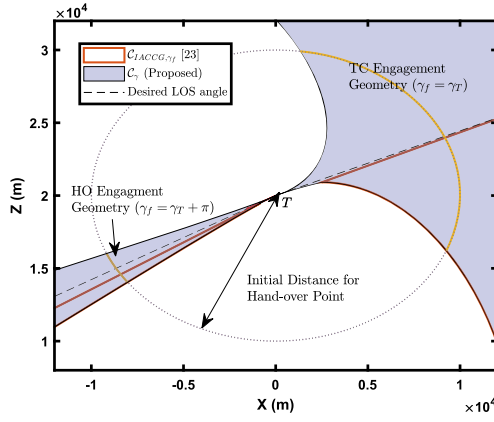
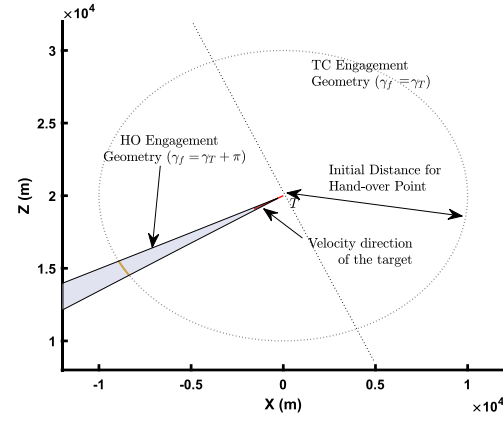
(a) Capture Region (Slow Target, $\gamma_f = 30$ deg)(b) Capture Region (Fast Target, $\gamma_f = 30$ deg)

Fig. 5. Capture Regions of Proposed Guidance Law for Slow-/Fast-Target Interception.

Eq. (39) indicates that C_{IACCG, γ_f} is the particular case of C_{γ_f, σ_c} when $\sigma_c = \underline{\sigma}$. Therefore, Eq. (40) can be easily understood. However, only HO engagement is feasible for interception, as shown in Fig. 5(b). The capture region is narrow compared with the capture region for HO engagement under a speed advantage. This implies that a speed disadvantage leads to a much harsher environment for interception, as expected.

5. Numerical simulations

We conducted numerical simulations using MATLAB R2024a Simulink on a system equipped with an i5 Quad-Core 1.4 GHz CPU and 8 GB of memory to demonstrate the effectiveness of the proposed guidance law. For simulation, the missile initiated engagement at the handover point, $r_0 = 10,000$ m, from the midcourse phase to the homing phase. The missile intercepted the target at a specified impact angle. We set the guidance parameters to $N = 6$, $(k, p) = (10, 0.5)$, and $(k_1, k_2) = (0.5, 0.2)$. The acceleration and FOV limits were set to $a_{\max} = 20g$ and $\sigma_{\lim} = 5$ deg, respectively. The missile dynamics were modeled using first-order approximation $a_m/a_{cmd} = \frac{1}{\tau s + 1}$, where time constant τ was set to 20 Hz.

5.1. Scenario 1: Slower-target interception

In this scenario, the speeds of the missile and target were set as $V_m = 700$ m/s and $V_T = 300$ m/s, respectively. It was required that the missile intercepted the approaching/retracting targets at a specified impact angle, $\gamma_f = 35$ deg. Two initial positions were selected per engagement scenario: $\lambda_0 = [25, 35]$ degrees for HO engagements and $\lambda_0 = [0, 35]$ degrees for TC engagements. Comparisons were conducted using PPNG and pursuit as benchmark laws to evaluate the effectiveness of the proposed method.

Fig. 6 shows the trajectories of the target and missiles for scenario 1. In this scenario, missiles from case 1-1 to 1-6 are designated to intercept the approaching target, while those from case 1-7 to 1-12 are tasked with pursuing the retracting target. The simulation results are presented in Figs. 7(a)–7(f). Pursuit guidance demonstrates effectiveness in intercepting retracting targets during the TC scenarios shown in Figs. 7(b) and 7(d). However, it exhibits instability near collisions and fails to hit targets in HO engagements. While PPNG leads to successfully intercepting both approaching and retracting targets, it struggles to maintain the desired impact angles. Notably, PPNG in case 1-9 makes the look angle exceed its limit during the maneuver shown in Fig. 7(d). These findings suggest that while the homing maneuver governed by PPNG is advantageous, a preceding look-angle control maneuver is necessary to ensure compliance with FOV limits and impact-angle constraints.

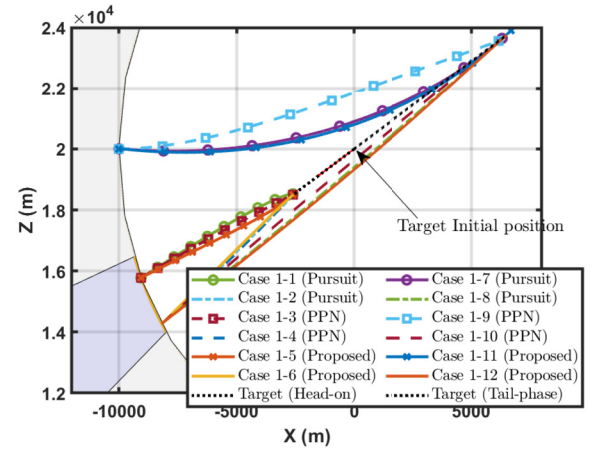


Fig. 6. Trajectories of Missiles and Target in Scenario 1.

Using the proposed method, the missile achieves the guidance objective. Fig. 6 highlights the extended capture region for a retracting target facilitated by the proposed method. To intercept the approaching target, the proposed guidance law generates appropriate look-angle commands based on the initial position. These commands guide the look angle until the guidance command switches, as illustrated in Fig. 7(a). These results demonstrate the superiority of the two-phase guidance scheme with the proposed command governor over benchmark laws. The proposed method not only outperforms in both HO and TC engagements but also extends the capture region, particularly in scenarios involving slower targets.

5.2. Scenario 2: Faster-target interception

We also considered a target that moved faster than the missile. The speeds of the missile and target were set to $V_m = 500$ m/s and $V_T = 700$ m/s, respectively. To intercept a faster target, the missile should initially be in front of the target, corresponding to an HO engagement geometry. The missile must intercept the approaching target at $|\gamma_f - \gamma_T| = 180$ deg. The desired terminal impact angle was $\gamma_f = 30$ deg. The initial positions for engagement were selected in the capture region obtained using Eq. (40), and the look angle and initial distance were set to $\sigma_0 = 0$ deg and $r_0 = 10,000$ m, respectively. For comparison, the composite guidance law in [23] was considered:

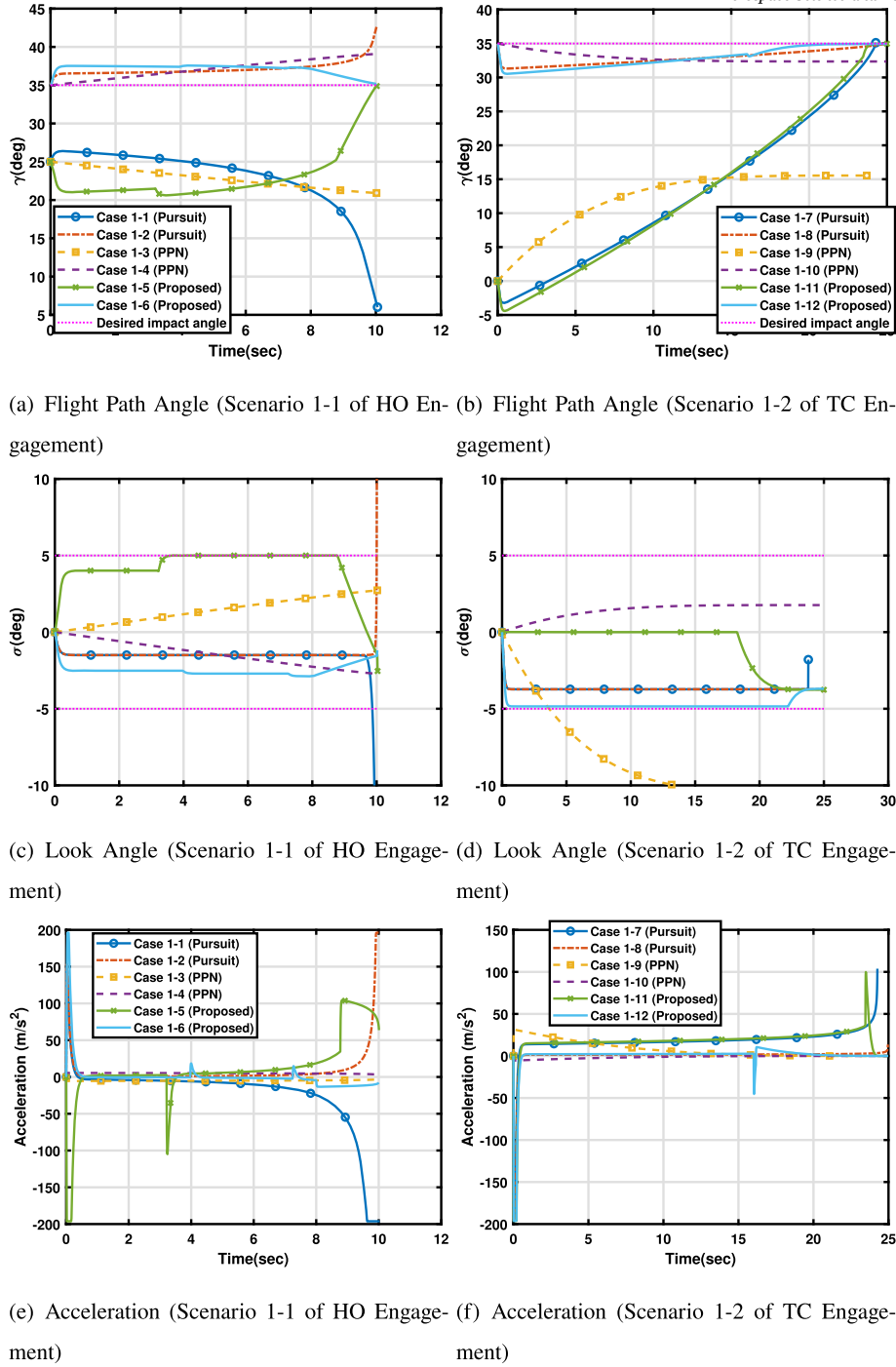


Fig. 7. Simulation Results of Scenario 1 (Slower-Target Interception).

$$a_{composite} = \begin{cases} V_m \dot{\lambda} + k V_m (-\sigma_{lim} - \sigma) & |\lambda - \lambda_f| > |\lambda_s - \lambda_f| \\ N V_m \dot{\lambda} & |\lambda - \lambda_f| \leq |\lambda_s - \lambda_f| \end{cases} \quad (41)$$

In the comparison guidance law, the look angle was maintained at the minimum value, and the guidance gains were set to $(N, k) = (5, 10)$ for a fair comparison.

In a more realistic scenario, a simulation was performed considering the target uncertainty, where the true state variables and measurements were polluted by noise. To handle noise, a target-tracking filter based on an extended Kalman filter (EKF) was integrated into the proposed guidance system. The system model for the EKF is provided in Appendix C, and the design procedure is detailed in [40].

Table 3
Comparison of Capture-Region Bounds.

Method	Cases	Capture region (LOS-Angle Range (°))
Ref. [23]	2-1, 2-2	$C_{IACCG_{\gamma_f}} = [31.24, 32.72]$
Proposed	2-3, 2-4, 2-5, 2-6	$C_{\gamma_f} = [27.10, 32.72]$

Cases 2-1 and 2-2 correspond to the guidance scheme presented in [23], while Cases 2-3 and 2-4 correspond to the switching guidance scheme but incorporate the proposed command generation in an ideal scenario. For a more realistic scenario, Cases 2-5 and 2-6 use the proposed guidance system with the EKF to handle target uncertainty. Fig. 8

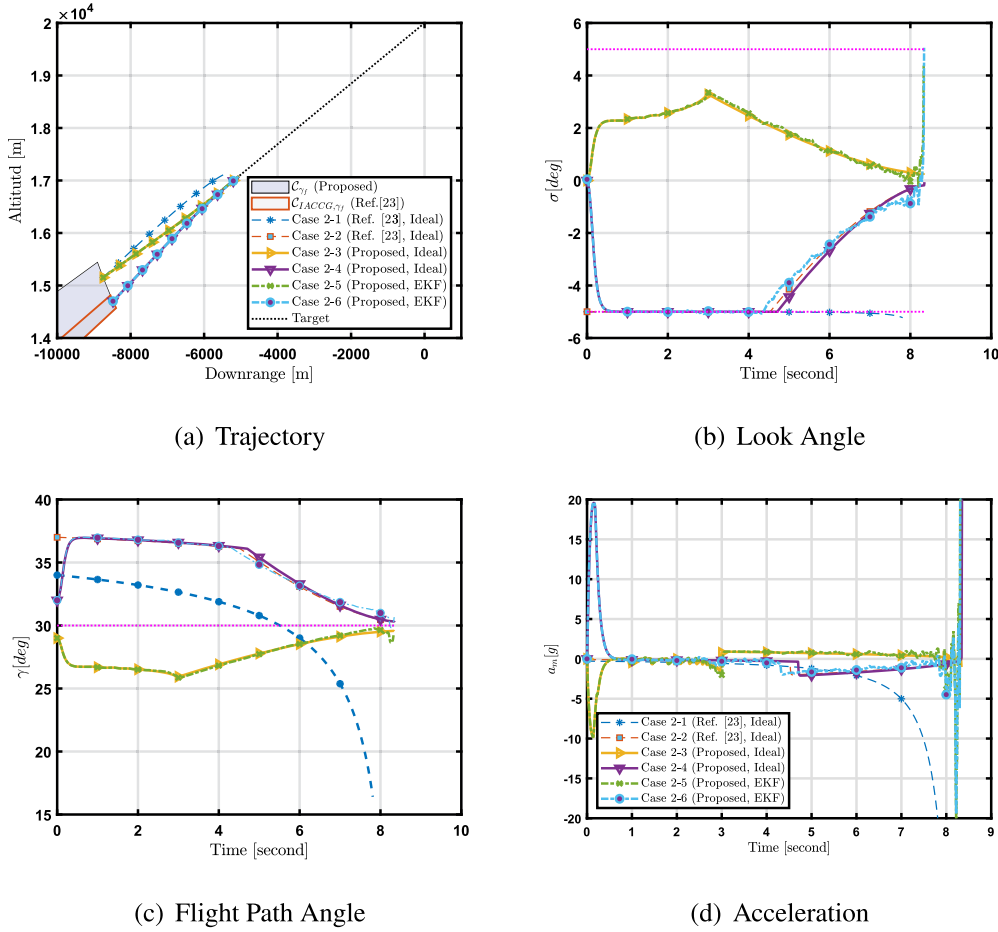


Fig. 8. Simulation Results for Faster-Target Interception (Scenario 2).

Table 4

Miss Distance, Look Angle, and Impact Angle (Scenario 2: Faster-Target Interception).

Case	Guidance	t_f (s)	r_f/R_{miss}	$ \sigma_f/\sigma_{\text{lim}} $	$\gamma_{\text{imp}} - \gamma_{\text{imp}}^d (^\circ)$
2-1	Ideal [23]	Miss	67.403	1.035	13.524
2-2	Ideal [23]	8.350	0.801	1.000	-0.366
2-3	Proposed (ideal)	8.340	0.501	0.657	0.450
2-4	Proposed (ideal)	8.350	0.809	1.000	-0.380
2-5	Proposed w/EKF	8.330	0.726	0.875	0.628
2-6	Proposed w/EKF	8.340	0.370	1.000	0.665

presents the simulation results, and Table 3 summarizes the capture region bounds for the scenario. Given the initial distance r_0 , the capture region under Ref. [23] is significantly limited, whereas the proposed scheme yields a substantially larger capture region, allowing for a wider range of initial positions, as illustrated in Fig. 8(a). To intercept an approaching target, the composite guidance law in [23] enables target interception only if the missile is initially in a narrow capture region, as in Case 2-2. Otherwise, the guidance command in Case 2-1 unnecessarily steers the look angle to its minimum. Consequently, the missile cannot switch the guidance phases and fails to intercept the target.

The proposed guidance law exhibits an extended capture region, as shown in Fig. 8(a). In the first phase, the look-angle command is properly corrected, and the look angle is maintained within the range of the generated command according to the initial position, as shown in Fig. 8(b). Thus, a missile guided by the proposed command-generation method in the guidance loop can intercept the target with an exact HO impact angle, as shown in Fig. 8(c). Fig. 8(d) shows the acceleration over time. When measured in the MATLAB/Simulink-based simulation

environment, look-angle command generation (Algorithm 1) required approximately 0.012 seconds, while the guidance command calculation took 0.004 seconds, equivalent to the computation required by the guidance law in Ref. [23]. Although the proposed algorithm includes additional computations, these computational timings indicate that the proposed guidance algorithm maintains a sufficiently low computational burden. This confirms that the proposed approach offers enhanced performance while remaining suitable for real-time implementation on typical onboard missile processors. In a realistic scenario with target uncertainty, the EKF-integrated guidance system exhibits responses similar to the ideal case when the target measurements are polluted by noise. The proposed guidance law incorporates state estimates to generate the guidance command, and interception with the exact impact angle can be achieved even under uncertainty. The EKF generates state estimates and compensates for the inaccurate target information polluted by sensor and process noise. However, compared with the ideal cases, the error of the estimates affects the performance of the guidance system near interception. Estimation errors, along with a considerable closing speed, render the guidance loop unstable as t_{go} decreases. Therefore, an advanced tracking filter design is required to mitigate instability. Table 4 summarizes the miss distance and error of the impact angle for fast-target interception.

6. Conclusions

A command governor for two-phase IAC guidance was designed considering the seeker FOV and acceleration constraints. Within the switching guidance scheme, the proposed add-on command governor effectively generated the look-angle command, facilitating the interception of fast targets at a specified impact angle. This innovation enhanced

the adaptability and applicability of baseline switching guidance law to air-to-air engagement. The derived capture region provided valuable insights into determining a suitable handover point from the midcourse phase to the homing phase. Future work will extend the command governor to 3D motion by utilizing adaptive approach to predict target motion for the maneuvering threats and explore reachability-based control for safety-critical, state-constrained scenarios. Additionally, hardware-in-loop tests and experimental studies will be conducted to bridge theory and practice.

CRedit authorship contribution statement

Seokwon Lee: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Namhoon Cho:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Youdan Kim:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Proof of finite-time convergence of look-angle error dynamics

Consider the error dynamics obtained by substituting Eq. (3) into Eq. (1c) as

$$\dot{e} = \dot{\sigma} - \dot{\sigma}_c = \dot{\lambda} - \frac{a_{cmd}}{V_m} = -k|e|^p \text{sign}(e) \quad (\text{A.1})$$

To show the finite-time convergence property of the error dynamics, a quadratic form of the error is considered as the Lyapunov candidate function.

$$V = \frac{1}{2}e^2 \quad (\text{A.2})$$

The time derivative of the Lyapunov candidate function along the error dynamics gives

$$\dot{V} = e\dot{e} = -k|e|^{p+1} = -k(2V)^{\frac{p+1}{2}} \quad (\text{A.3})$$

which is rewritten as

$$\frac{dV}{V^{\frac{p+1}{2}}} = -k2^{\frac{p+1}{2}} dt \quad (\text{A.4})$$

Integrating by parts gives

$$\frac{2}{1-p} \left((V(t))^{\frac{1-p}{2}} - (V(0))^{\frac{1-p}{2}} \right) = -k2^{\frac{p+1}{2}} t \quad (\text{A.5})$$

Note that $V(0) = \frac{1}{2}|e|^2$,

$$(V(0))^{\frac{1-p}{2}} = |e(0)|^{1-p} 2^{\frac{p-1}{2}} \quad (\text{A.6})$$

$$k2^{\frac{p+1}{2}} \frac{1-p}{2} = k(1-p)2^{\frac{p-1}{2}} \quad (\text{A.7})$$

$$(V(t))^{\frac{1-p}{2}} = \begin{cases} 2^{\frac{p-1}{2}} (|e(0)|^{1-p} - k(1-p)t) & t \leq T \\ 0 & t \geq T \end{cases} \quad (\text{A.8})$$

$V(t)$ becomes zero when $t = T$, where

$$(V(T))^{\frac{1-p}{2}} = 2^{\frac{p-1}{2}} (|e(0)|^{1-p} - k(1-p)T) = 0 \quad (\text{A.9})$$

Therefore, the error converges to zero in finite time $T = \frac{|e(0)|^{1-p}}{k(1-p)}$.

Appendix B. Proof of Proposition 1

Eqs. (13) and (14) can be rewritten as follows:

$$\lambda_{TC}^*(\sigma_c) = \gamma_T + \delta, \quad \lambda_{HO}^*(\sigma_c) = \gamma_T + \pi - \delta \quad (\text{B.1})$$

where $\delta = \sin^{-1}(\sin \sigma_c / \eta)$. Let $\theta_{TC} = \lambda - \lambda_{TC}^*(\sigma_c)$ be the deviation of the LOS angle from the equilibrium point. From the definition of Λ_{TC} and Eq. (B.1), set Θ_{TC} can be defined as

$$\Theta_{TC} = \{\theta_{TC} | -\pi/2 - \delta \leq \theta_{TC} \leq \pi/2 - \delta\} \quad (\text{B.2})$$

Consider the following Lyapunov candidate function:

$$V_{TC} = \frac{1}{2}\theta_{TC}^2 \quad (\text{B.3})$$

Differentiating V_{TC} with respect to time and using Eq. (B.3) in the resulting equation yield

$$\dot{V}_{TC} = \dot{\theta}_{TC}\theta_{TC} = \frac{V_T}{r} f_{TC}\theta_{TC} \quad (\text{B.4})$$

where

$$f_{TC} = \sin(\gamma_T - \lambda) + \frac{1}{\eta} \sin \sigma_c \quad (\text{B.5})$$

Note that $\gamma_T = \lambda_{TC}^*(\sigma_c) - \delta = \lambda - \theta_{TC} - \delta$. Eq. (B.5) can be rewritten as

$$\begin{aligned} f_{TC} &= -\sin(\theta_{TC} + \delta) + \frac{1}{\eta} \sin \sigma_c \\ &= -\sin \theta_{TC} \cos \delta + (1 - \cos \theta_{TC}) \sin \delta \\ &= -\sin(\theta_{TC} + \delta) + \sin \delta \end{aligned} \quad (\text{B.6})$$

Substituting $\theta_{TC} = 0$ into Eq. (B.6) gives $f_{TC}(0) = 0$. In addition, f_{TC} is a decreasing function with respect to θ_{TC} because

$$\frac{\partial f_{TC}}{\partial \theta_{TC}} = -\cos(\theta_{TC} + \delta) < 0 \quad (\text{B.7})$$

for $\theta_{TC} \in \Theta_{TC}$, Eq. (B.2). Therefore, the sign of f_{TC} according to θ_{TC} can be expressed as

$$f_{TC} = \begin{cases} > 0 & \theta_{TC} < 0 \\ = 0 & \theta_{TC} = 0 \\ < 0 & \theta_{TC} > 0 \end{cases} \quad (\text{B.8})$$

Finally, multiplying θ_{TC} by Eq. (B.8) gives $f_{TC}(\theta_{TC})\theta_{TC} < 0$. Thus, $\dot{V}_{TC}$ is negative definite.

Set Θ_{HO} can be defined using the definition of Λ_{HO} and Eq. (B.1) as follows:

$$\Theta_{HO} = \{\theta_{HO} | -\pi/2 + \delta \leq \theta_{HO} \leq \pi/2 + \delta\} \quad (\text{B.9})$$

Consider the following Lyapunov candidate function for HO engagement:

$$V_{HO} = \frac{1}{2}\theta_{HO}^2 = \frac{1}{2}(\lambda - \lambda_{HO}^*(\sigma_c))^2 \quad (\text{B.10})$$

By taking the time derivative of the Lyapunov candidate function $\dot{V}_{HO}$, we obtain

$$\dot{V}_{HO} = \dot{\theta}_{HO}\theta_{HO} = \frac{V_T}{r} f_{HO}\theta_{HO} \quad (\text{B.11})$$

where f_{HO} can be expressed as a function of θ_{HO} using $\gamma_T = \lambda_{HO}^* - \pi + \delta$:

$$\begin{aligned} f_{HO} &= \sin(\pi - \theta_{HO} + \delta) + \frac{1}{\eta} \sin \sigma_c \\ &= \sin(\theta_{HO} - \delta) + \sin \delta \end{aligned} \quad (\text{B.12})$$

Substituting $\theta_{HO} = 0$ into Eq. (B.12) yields $f_{HO}(0) = 0$. Additionally, f_{HO} is an increasing function with respect to θ_{HO} because

$$\frac{\partial f_{HO}}{\partial \theta_{HO}} = \cos(\theta_{HO} - \delta) > 0 \quad (\text{B.13})$$

for $\theta_{HO} \in \Theta_{HO}$, Eq. (B.9). Therefore, the sign of f_{HO} according to θ_{HO} can be expressed as

$$f_{HO} = \begin{cases} < 0 & \theta_{HO} < 0 \\ = 0 & \theta_{HO} = 0 \\ > 0 & \theta_{HO} > 0 \end{cases} \quad (\text{B.14})$$

Finally, $f_{HO}(\theta_{HO})\theta_{HO} > 0$ gives the positive definiteness of $\dot{V}_{HO}$.

Appendix C. System model for EKF design

The relative position and velocity are considered as variables $x = [r_x \ r_y \ v_x \ v_y]^T$. The discrete system dynamics can be expressed as

$$x_k = \Phi x_{k-1} + \Gamma u_{k-1} + w \quad (\text{C.1})$$

$$\Phi = \begin{bmatrix} I_{2 \times 2} & \Delta t I_{2 \times 2} \\ 0_{2 \times 2} & I_{2 \times 2} \end{bmatrix}, \quad \Gamma = \begin{bmatrix} (\Delta t^2/2)I_{2 \times 2} \\ \Delta t I_{2 \times 2} \end{bmatrix} \quad (\text{C.2})$$

where $u_k = [a_x, a_y]$ is the missile acceleration expressed in the inertial coordinates and Δt is the sampling period of the guidance filter, which is set to 0.01 s. For the measurement model, the range and LOS angle are considered.

$$z_k = h(x_k, v_k) = \begin{bmatrix} \sqrt{r_x^2 + r_y^2}(1 + v_1) \\ \tan^{-1}(r_y/r_x)(1 + v_2) \end{bmatrix} \quad (\text{C.3})$$

We assume that the measurements are polluted by 5% multiplicative noise. The covariance matrices of the process and measurement models are expressed as

$$Q = \sigma^2 \begin{bmatrix} (\Delta t^3/3)I_{2 \times 2} & (\Delta t^2/2)I_{2 \times 2} \\ (\Delta t^2/2)I_{2 \times 2} & (\Delta t)I_{2 \times 2} \end{bmatrix}, \quad R = \begin{bmatrix} 0.05^2 & 0 \\ 0 & 0.05^2 \end{bmatrix} \quad (\text{C.4})$$

The initial estimates and error covariances are set as follows:

$$\hat{x}_0 = \begin{bmatrix} r_x(0) + \text{randn}(100) \\ r_y(0) + \text{randn}(100) \\ v_x(0) + \text{randn}(10) \\ v_y(0) + \text{randn}(10) \end{bmatrix}, \quad \hat{P}_0 = \text{diag}([10^2, 10^2, 1^2, 1^2]) \quad (\text{C.5})$$

Data availability

No data was used for the research described in the article.

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