

UDC 629.7.052:681.5(045)
DOI:10.18372/1990-5548.88.20981

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COMPARATIVE ANALYSIS OF METHODS OF GUIDING AIRCRAFT TO MANEUVERING TARGETS

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Abstract—This article analyzes modern methods for guiding aircraft toward maneuvering targets. The main guidance algorithms are considered, in particular geometric methods, the proportional guidance method, and its modifications. Based on a kinematic model of the relative motion of the interceptor and the target, the principles of generating control accelerations and the specifics of the practical implementation of the corresponding algorithms are analyzed. A comparative analysis of the considered methods is conducted in terms of their effectiveness, implementation complexity, and ability to ensure the interception of maneuvering targets. It is shown that the proportional guidance method is the most widespread in modern systems; however, its effectiveness may decrease in the case of active target maneuvering and the presence of measurement errors. It has been established that modified guidance algorithms, in particular Augmented Proportional Navigation, require estimation of the target's acceleration, which in real-world conditions is accompanied by measurement uncertainty and noise. This paper identifies the main limitations of existing approaches and justifies the development of adaptive guidance methods capable of accounting for the uncertainty of target motion parameters and the dynamic limitations of control systems.

Keywords—Aircraft guidance, maneuvering target, proportional guidance, guidance algorithms, interception.

1. INTRODUCTION

Guidance systems are one of the key elements in the control of modern aircraft designed to intercept or track moving targets. Their primary purpose is to generate control commands that ensure the aircraft approaches the target with minimal error [1], [2]. The effectiveness of such systems largely determines the overall success of interception missions [3], [4].

Guidance methods are widely used in various classes of aircraft, including guided missiles, unmanned aerial vehicles, and other autonomous motion control systems. In such systems, guidance algorithms are used to generate a flight path that ensures the target is reached or the required distance to it is maintained [5].

The guidance task becomes significantly more complex when the target performs active maneuvers or changes its motion parameters during the interception process. Maneuvering introduces additional uncertainties in the relative motion of objects, which complicates the prediction of the point of encounter and may reduce the effectiveness of classical control algorithms.

A significant number of different approaches and algorithms have been proposed to solve guidance problems, differing both in the principles of generating control actions and in the complexity of

implementation. Among the most well-known are proportional guidance methods and their modifications, algorithms that account for target acceleration, optimal control methods, as well as adaptive approaches capable of changing their parameters depending on flight conditions [6].

The existence of a large number of guidance methods necessitates their systematization and comparative analysis in terms of effectiveness of application under conditions of target maneuvering and the limitations of real-world control systems.

II. OVERVIEW OF CURRENT ALIGNMENT METHODS

A. General formulation of the guidance problem

The task of guiding an interceptor is to formulate a control law that ensures the aircraft approaches the target with a specified accuracy, subject to constraints on the system's dynamic characteristics. A two-dimensional kinematic model of the motion of the interceptor and the target is considered. Let the position of the interceptor be defined by the coordinates (x_m, y_m) , and target (x_t, y_t) .

The relative position is described by a vector:

$$\vec{r} = \begin{bmatrix} x_t - x_m \\ y_t - y_m \end{bmatrix},$$

where x_m, y_m are interceptor's coordinates; x_t, y_t are target coordinates.

The distance between objects is defined as

$$r = \sqrt{(x_t - x_m)^2 + (y_t - y_m)^2},$$

where r is the distance between the interceptor and the target.

The angle of the line of sight is defined as

$$\lambda = \arctan \frac{y_t - y_m}{x_t - x_m},$$

where λ is the angle of the line of sight, rad.

The guidance task involves generating lateral acceleration for the interceptor a_m , which reduces the distance $r \rightarrow 0$.

Figure 1 shows the geometry of the problem of guiding an interceptor to a target in a plane.

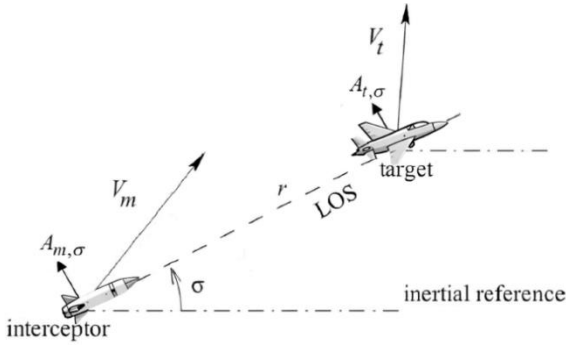


Fig. 1. Geometry of the interaction between the interceptor and the target

The following symbols are used in this model:

- V_m is the interceptor speed, m/s;
- V_t is the target velocity, m/s;
- $A_{m,\sigma}$ is the lateral acceleration of the interceptor in the direction perpendicular to the velocity vector, m/s²;
- $A_{t,\sigma}$ is the lateral acceleration of the target, m/s²;
- r is the distance between the interceptor and the target (range), m;
- LOS (Line of Sight) is the line of sight connecting the interceptor and the target;
- σ is the angle of the line of sight relative to the inertial coordinate system, in radians.

B. The Pure Pursuit Method

The direct tracking method is one of the simplest guidance algorithms. In this case, the

direction of the interceptor's velocity is constantly aligned with the target's current position.

The control law can be expressed as:

$$\psi_m = \lambda,$$

where ψ_m is the angle of the interceptor's course, rad; λ is the angle of the line of sight, rad.

The corresponding lateral acceleration is calculated as a function of the difference in angles:

$$a_m = K_{pp} V_m (\lambda - \psi_m),$$

where a_m is the lateral acceleration of the interceptor, m/s²; K_{pp} is the gain; V_m is the interceptor speed, m/s.

This method does not take into account the target's future trajectory, which leads to the generation of irrational trajectories and increased demands on control accelerations [7], [8].

C. The Proportional Navigation Method (PN)

The proportional guidance method is based on the use of the angular velocity of the line of sight. The basic idea is to generate a control acceleration that ensures the rotation of the interceptor's velocity vector is proportional to the angular velocity of the line of sight [9].

The control law is given by:

$$a_m = N V_c \dot{\lambda},$$

where a_m is the lateral acceleration of the interceptor, m/s²; N is the navigation constant; V_c is the approach speed, m/s; $\dot{\lambda}$ is the angular velocity of the line of sight, rad/s.

The approach velocity is defined as

$$V_c = -\frac{dr}{dt},$$

where V_c is the approach speed, m/s; r is the distance between objects, m.

The PN method provides a more efficient interception trajectory compared to geometric methods, but does not account for the target's lateral acceleration [10].

D. Modified Adaptive Proportional Navigation (APN)

To improve the accuracy of intercepting maneuvering targets, a modified proportional guidance method is used that takes into account the

target's lateral acceleration. The control law is given by [11]:

$$a_m = NV_c \dot{\lambda} + k_a a_t,$$

where a_m is the lateral acceleration of the interceptor, m/s²; N is the navigation constant; V_c is the approach speed, m/s; $\dot{\lambda}$ is the angular velocity of the line of sight, rad/s; k_a is a compensation factor; a_t is the lateral acceleration of the target, m/s².

In theory, taking the target's acceleration into account can reduce the tracking error. However, the effectiveness of the method depends on the accuracy of the measurement a_t and the nature of how this parameter changes over time [12].

III. COMPARISON OF EXISTING ALIGNMENT METHOD

To conduct a comparative analysis of the guidance algorithms under consideration, a numerical simulation of the interception process of a maneuvering target was performed. The purpose of the simulation is to evaluate the effectiveness of various guidance laws in terms of interception accuracy and requirements for control accelerations [13].

A. Conditions for numerical modeling

The simulation was based on a kinematic model of the relative motion between the interceptor and the target in a plane. It was assumed that the magnitudes of the objects' velocities remained constant, and that changes in direction were determined by lateral accelerations.

The initial conditions were specified as follows: the interceptor's velocity $V_m = 250$ m/s, target velocity $V_t = 180$ m/s. The interceptor's initial position is (0, 0), direction of motion $\psi_m = 90^\circ$. Initial position of the target: (-1500, 2000), direction of movement $\psi_t = 5^\circ$.

To simulate a complex interception scenario, the target performed a sequence of intense maneuvers specified as piecewise-continuous lateral acceleration:

- $a_t = 16$ m/s² in interval 4–5.5 s;
- $a_t = -16$ m/s² in interval 5.5–7 s;
- $a_t = 20$ m/s² in interval 7–10 s.

This scenario allows for an assessment of the effectiveness of guidance algorithms under conditions of rapidly changing target motion patterns.

B. Comparative interception trajectories

Figure 2 shows the interceptor's flight paths when using the Pure Pursuit, Proportional Guidance (PN), and modified APN methods.

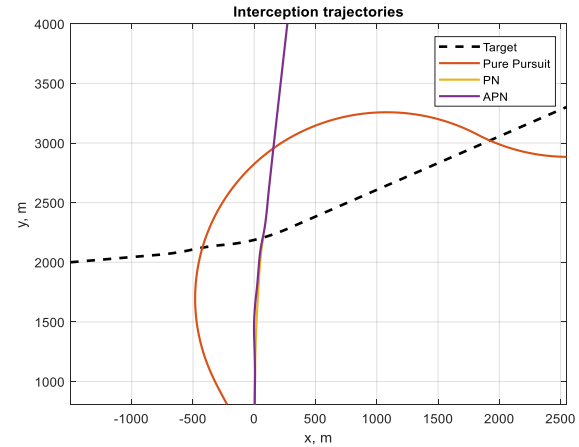


Fig. 2. Interception trajectories for different guidance methods

An analysis of the resulting trajectories shows that each of the methods considered demonstrates satisfactory performance only under specific conditions, whereas their inherent limitations become apparent during complex maneuvers.

The Pure Pursuit method generates a significantly distorted interceptor trajectory, leading to an increased path length and inefficient use of the aircraft's dynamic capabilities.

The Proportional Guidance (PN) method provides a more consistent approach trajectory. However, its effectiveness is based on the assumption of relatively smooth target motion, and during complex maneuvers, it does not guarantee a minimum interception error.

The modified APN method, which accounts for target acceleration, has theoretical advantages. However, in the scenario under consideration, with rapid changes in maneuvering, trajectory instability is observed, leading to a deterioration in guidance performance.

Thus, none of the methods considered ensures consistently high performance under conditions of complex target maneuvering.

C. Analysis of the time-to-target

Figure 3 shows the dependence of the distance between the interceptor and the target on time.

Analysis of the obtained dependencies shows that the behavior of the guidance system depends significantly on the nature of the target's motion.

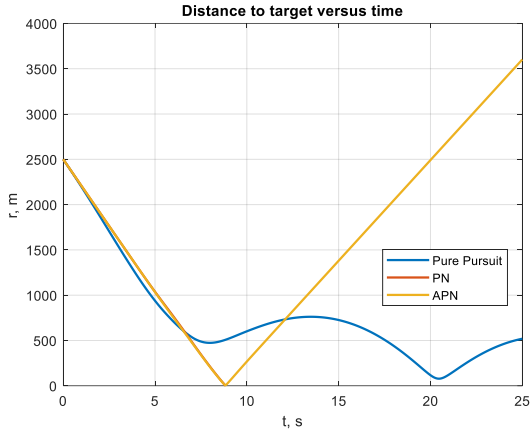


Fig. 3. Change in distance to the target over time

The Pure Pursuit method exhibits an oscillatory convergence pattern, indicating the ineffectiveness of this approach under conditions of active maneuvering.

The Proportional Guidance (PN) method ensures a more stable reduction in the distance to the target, but does not account for the variable nature of the target's acceleration.

The APN method proves to be sensitive to rapid changes in acceleration, which can lead to a loss of effectiveness even when additional information about the target's motion is available.

D. Analysis of lateral acceleration control

Figure 4 shows the variation of the interceptor's commanded lateral acceleration over time.

An analysis of control accelerations reveals fundamental differences in the nature of control action generation for various guidance methods.

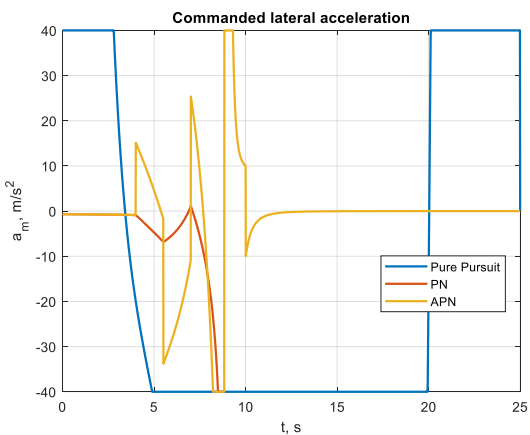


Fig. 4. Interceptor's lateral control acceleration

The Pure Pursuit method requires significant lateral acceleration values, which is due to the need for constant course correction without taking into account the target's future behavior. This leads to

increased loads on the aircraft structure and the control system actuators.

The Proportional Guidance method generates more coordinated control actions that correspond to the intercept geometry. This allows for a reduction in maximum acceleration values and an increase in the efficiency of utilizing the interceptor's dynamic capabilities.

The APN method, despite accounting for the target's acceleration, exhibits abrupt changes in control inputs during rapid maneuver changes. This indicates its heightened sensitivity to target dynamics and may negatively affect the stability of the control system.

Thus, accounting for target acceleration alone does not guarantee improved guidance quality and requires additional information processing.

E. Quantitative analysis of the results

To summarize the simulation results, a quantitative assessment of the effectiveness of the guidance methods was performed based on the following indicators:

- minimum distance to the target r_{\min} ;
- maximum controllable acceleration a_{\max} ;
- comprehensive assessment of management practices

$$J = \int |a_m(t)| dt.$$

The results of the analysis confirm that the Pure Pursuit method is characterized by the highest consumption of control resources and significant computational loads.

The proportional guidance method ensures more balanced system behavior, but does not account for the variable nature of the target's motion.

The modified APN method may lose effectiveness in the case of complex maneuvers, despite the use of additional information about the target's motion.

IV. ANALYSIS OF LIMITATIONS AND PROSPECTS FOR THE DEVELOPMENT OF ALIGNMENT METHODS

A. Limitations of the classical laws of induction

The classical laws of tracking, in particular the proportional tracking method, are based on the assumption that the target's motion is relatively smooth. In this case, the interceptor's control acceleration is defined as

$$a_m = NV_c \dot{\lambda},$$

where a_m is the lateral control acceleration of the interceptor, m/s²; N is the navigation constant; V_c is the rate of approach between the interceptor and the target, m/s; $\dot{\lambda}$ is the angular velocity of the line of sight, rad/s.

This approach does not account for the target's lateral acceleration, which, in the case of active maneuvering, leads to additional guidance errors. As shown in Section 3, when the target's motion is complex, the effectiveness of the PN method depends on the choice of the parameter N and does not guarantee that the control actions are optimal.

B. Limitations of modified methods (APN)

A modified proportional guidance law is used to compensate for the target's maneuvering:

$$a_m = NV_c \dot{\lambda} + k_a a_t,$$

where a_m is the lateral control acceleration of the interceptor, m/s²; N is the navigation constant; V_c is the approach speed, m/s; $\dot{\lambda}$ is the angular velocity of the line of sight, rad/s; k_a is the target acceleration compensation factor; a_t is the lateral acceleration of the target, m/s².

In theory, this approach allows for improved interception accuracy. However, the simulation results presented in Section 3 showed that, in the case of rapid changes in the target's acceleration, the APN method can exhibit unstable behavior.

This is because the direct use of the target's acceleration leads to the generation of abrupt control inputs. In the case of a rapidly changing or piecewise-defined maneuver, an overcompensation effect occurs, which can lead to an increase in guidance error or a failure of the interception.

C. Challenges in Estimating Target Maneuvering

In real guidance systems, the target's acceleration is typically not measured directly, but is estimated based on indirect measurements.

Let the measured value of the line-of-sight angle be defined as

$$\lambda_m(t) = \lambda(t) + \varepsilon(t),$$

where $\lambda_m(t)$ is the measured value of the sighting angle, radians; $\lambda(t)$ is the true angle of the line of sight, in radians; $\varepsilon(t)$ is the measurement error.

To determine the target's acceleration, it is necessary to calculate the derivatives of the measured quantities, which leads to an increase in noise:

$$a_t \sim \frac{d^2\lambda}{dt^2},$$

where a_t is the estimated lateral acceleration of the target, m/s²; λ is the angle of the line of sight, rad.

As a result, even minor measurement errors can significantly affect the accuracy of acceleration estimation, which directly impacts the quality of control actions in methods such as APN.

D. Dynamic constraints in control systems

Under actual operating conditions, the generation of steering acceleration is limited by the dynamics of the autopilot and the actuators.

The dynamics of the control system can be described by the equation:

$$\tau \dot{a}_m + a_m = a_{cmd},$$

where τ is the time constant of the control system, s; a_m is the actual lateral acceleration of the interceptor, m/s²; \dot{a}_m is the acceleration change rate, m/s³; a_{cmd} is the set (command) acceleration, m/s².

The presence of inertia causes delays in the execution of control commands. In the case of rapid maneuvers, this can lead to a discrepancy between the calculated and actual trajectories.

E. Prospects for the Development of Adaptive Guidance Methods

Given the identified limitations, the development of adaptive guidance algorithms represents a promising direction.

Such algorithms must ensure:

- real-time adjustment of guidance law parameters;
- accounting for the intensity of the target's maneuvering;
- reduction of the impact of measurement errors;
- alignment of control inputs with the aircraft's dynamic capabilities.

One possible approach is the use of a variable navigation constant $N = N(t)$, which adapts depending on the approach conditions.

Thus, the further development of guidance methods is associated with the transition to adaptive control structures capable of operating under conditions of uncertainty and variable dynamics.

V. CONCLUSIONS

This paper presents a comparative analysis of the main methods for guiding an interceptor to a maneuvering target, specifically Pure Pursuit, Proportional Guidance (PN), and its modification,

APN. Based on numerical simulations, it is shown that the effectiveness of each method depends significantly on the nature of the target's motion and the interception conditions.

It has been established that geometric methods are characterized by increased requirements for control accelerations, the proportional guidance method does not account for the target's acceleration, and modified methods such as APN are sensitive to rapid changes in maneuvering and estimation errors.

The results confirm that none of the approaches considered ensures universal effectiveness under conditions of complex target maneuvering.

Thus, the necessity of developing adaptive guidance methods capable of accounting for the variable nature of the target's motion, measurement uncertainty, and limitations of the aircraft's dynamic capabilities is substantiated.

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Received: February 18, 2026

Accepted: March 10, 2026

Published: April 19, 2026

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О. М. Тачиніна, А. В. Коваленко. Порівняльний аналіз методів наведення літаків на маневрені цілі

У статті проаналізовано сучасні методи наведення літальних апаратів на маневрені цілі. Розглянуто основні алгоритми наведення, зокрема геометричні методи, метод пропорційного наведення та його модифікації. На основі кінематичної моделі відносного руху перехоплювача та цілі проаналізовано принципи формування керуючих прискорень та специфіку практичної реалізації відповідних алгоритмів. Проведено порівняльний аналіз розглянутих методів з точки зору їх ефективності, складності реалізації та здатності забезпечити перехоплення маневрених цілей. Показано, що пропорційний метод наведення є найбільш поширеним у сучасних системах; однак його ефективність може знижуватися у разі активного маневрування цілі та наявності похибок вимірювання. Встановлено, що модифіковані алгоритми наведення, зокрема Augmented Proportional Navigation, вимагають оцінки прискорення цілі, що в реальних умовах супроводжується невизначеністю вимірювання та шумом. У статті визначено основні обмеження існуючих підходів та обґрунтовано розробку адаптивних методів наведення, здатних враховувати невизначеність параметрів руху цілі та динамічні обмеження систем керування.

Ключові слова: наведення літального апарату, маневрена цілі, пропорційне наведення, алгоритми наведення, перехоплення.

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Напрямок наукової діяльності: методи оптимального керування динамічними системами і процесами.

Кількість публікацій: більше 130 публікацій.

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Напрямок наукової діяльності: ідентифікація складних систем.

Кількість публікацій: 6.

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