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Approaches to Optimizing Guidance Methods to High-Speed Intensively Maneuvering Targets. Part I. Justifying Requirements for Ways to Optimize Guidance Methods

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Abstract—High-speed aircraft capable of complex spatial maneuvers and having several technical, economic, and tactical advantages are increasingly used in aerospace warfare. In this regard, a topical problem is to optimize interception systems for such targets. The operation features of interception systems are considered based on analyzing flight path features of high-speed aircraft. Requirements for ways to optimize guidance methods are formulated.

Keywords: high-speed aircraft, complex maneuver, interception system, guidance method, optimization, statistical theory of optimal control, inverse dynamics problems, gradient method, intelligent control

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1. INTRODUCTION

The analysis of military-technical counteraction features in aerospace warfare [1] revealed the growing role and importance of high-speed aircraft (HSA) [2] capable of complex spatial maneuvers. Using such aircraft as a weapon ensures several technical, economic, and tactical advantages in warfare [3].

The technical and economic advantages are due to a very high cost of developing and operating counteraction systems, in terms of human, material, financial, and time resources, compared to the cost of HSA manufacturing and using it as a weapon.

The HSA tactical advantages are due to the following factors [3]:

- a significant reduction in the time to reach the target (consequently, in the time to prepare counteraction), which makes it necessary to increase the range of interception systems;
- a qualitative reduction in the arsenal of possible interception means;
- the practical impossibility of providing all-sector interception;
- the qualitative deterioration of conditions for HSA detection and tracking;
- the inability of conventional homing methods to ensure effective interception;
- the ability to simultaneously realize high-level indicators of target hitting efficiency, survivability, and dynamism.

In this regard, it is in increasing demand to develop advanced HSA interception systems capable of leveling these advantages. Note that the operation of such systems should be based primarily on improved guidance methods and their information support procedures. Therefore, it is necessary to analyze the capabilities of various optimization methods to develop next-generation guidance methods for HSA interception.

In this paper, we study the features of hypothetical HSA interception systems, justify requirements for ways to optimize guidance methods, and qualitatively analyze their capabilities.

2. FEATURES OF HSA INTERCEPTION SYSTEMS

HSA interception systems shall provide:

— stable control of the interceptor at long ranges when the target performs complex maneuvers within admissible constraints on the value of control signals;

— control that prevents exceeding stability loss bounds during maneuvers;

— stable guidance when the interceptor is subjected to various disturbances;

— guidance as part of a group;

— control implementability.

The high speed of HSA predetermines, first of all, the need to consider its impact on the effectiveness of interception systems. It is primarily due to increased delays in the interceptor's response to target maneuvers caused by its inertia. In addition, the high speed of HSA predetermines the need to increase the range of interception systems to compensate for the reduction in the time to prepare counteraction. In turn, extending the range of interception systems leads to a qualitative decrease in the line-of-sight angle rate, which is the main information parameter of most existing homing methods [4–7]. In view of this feature, it is necessary to use nonstationary guidance methods [8]; when implementing these methods, angular errors in the direction of flight are first eliminated, and then linear misses are eliminated based on minimizing the line-of-sight angle rate.

The complex spatial movements of high-speed targets with changing the sign of derivatives for relative and absolute motion parameters [9] predetermines several operation features of their interception systems:

- the ineffectiveness of using guidance methods to the most advantageous prediction collision point [4] due to its periodic displacement in space during target maneuvering;
- special measures taken to withdraw the carrier from stability loss bounds when it performs a maneuver to intercept the target [10];
- the use of high-order derivatives of angular coordinates in the guidance law to compensate for the interceptor's inertia [11];
- random guidance time [4].

Note that an HSA is most effectively used as part of a group. In this regard, a topical problem is to guide the interceptor individually to a target as part of a group [10–14]. In turn, this necessitates the use of path-based tracking control [10, 15–17]: the interceptor's guidance path shall ensure resolving the group members and identifying the target of interest (at the first stage) and performing guidance with miss minimization (at the second stage).

Under given constraints, implementability is provided by at least three conditions:

- the corresponding dynamic properties of the carrier characterizing its maneuverability;
- the ability to stably estimate all relative and absolute target motion coordinates used in the guidance method;
- the fulfillment of constraints on the operating range of state coordinates, control overloads of the carrier, and automatic tracking errors in angular and linear coordinates.

The high degree of uncertainty in the application conditions, the wide range of possible maneuvers and their unpredictability predetermine the imperfection of state models used in the design of guidance methods and their information support. In some cases, due to this feature, the results of measurements are directly used as the required coordinates in the control law, and the measurement errors reflect the actual state of the HAS–interceptor system.

The aircraft radar system applied as the main source of information predetermines the need to consider two features:

- the use of an open radio channel, which possibly receives various radio interference;
- the dependence of the accuracy and reliability of the resulting measurements on the geometry of the mutual location of the radar carrier and the target tracked.

This requires the generation of appropriate control signals by the carrier to perform the ultimate task and, moreover, ensure the best conditions for target tracking [10, 11]. The solution of the above problems depends largely on the optimization method used in the design.

3. JUSTIFYING REQUIREMENTS FOR THE MATHEMATICAL APPARATUS OF OPTIMIZATION

Adapting the carrier's dynamic properties to the requirements of the guidance method used is a very complex and expensive problem. In this regard, it is reasonable to optimize the guidance method for a ready-made carrier, compensating for its insufficient dynamism by additional correction signals based on high-order derivatives of angular coordinates. Note that the optimal estimation of the high-order derivatives of angular coordinates when measuring only relative bearing is also a rather difficult problem [9].

Countering high-speed weapons leads to several theoretical and applied problems of management and information support, which shall be solved when developing particular interception systems. The solution of these theoretical problems is based on the development (selection and justification) of an appropriate mathematical apparatus of optimization. The essence of solving applied problems consists in obtaining particular guidance and automatic target tracking methods based on the apparatus of optimization selected.

Therefore, it is of interest to assess (at least at a qualitative level) the potential of various ways of optimization when designing guidance methods for HSA interceptors.

Within any way of optimization [10–14, 18–22], one has to specify the following elements:

- criteria (rules) determining whether the system being optimized fits its purpose;
- perfection indicators (measures) qualitatively determining the preference for a particular scheme of an interceptor system under development;
- the set of constraints imposed on state coordinates and control signals;
- the class of initial state models to implement the set of tasks;
- the control signal type ensuring invariance with respect to application conditions;
- the complexity (speed) of forming control signals (within the selected criteria), indicators, and initial models;
- the set of optimal estimates of the state coordinates required to implement the guidance method.

Linearized time-varying models [10] are most reasonable to use from the viewpoint of the size of the application area in which acceptable adequacy to the application conditions and universality of the generated controls are achieved. Such models combine the advantages of linear and nonlinear representations.

In addition, the state models used shall describe different types of disturbances without augmenting the state vector.

The undoubted benefit of time-varying state models is the possibility of forming nonstationary guidance methods that allow changing control priorities during operation [5, 8]. It is reasonable to choose lateral accelerations as control signals to eliminate the dependence of control efficiency on height, which is characteristic of aerodynamic rudders.

Note that different schemes of control laws can be obtained even within one way of optimization, depending on the type of the initial model and the quality functional selected. The features of mathematical models in the state space, their classification and interrelation with optimization methods were discussed in detail in [10].

As a rule, target achievement results are used as performance indicators of the guidance methods of HSA interception: the current and final misses, guidance errors in angular coordinates, overloads, guidance time, etc.

In general, the set of constraints is determined by the range of coordinates served (range, speed, intercept sectors, allowable misses, etc.) and allowable overloads within which the system implements its purpose.

Summarizing the considerations above, we conclude that, when applied to the HSA interception problem, the mathematical apparatus of optimization shall provide:

- the possibility of forming nonstationary guidance methods capable of redistributing control priorities during the interception process;
- implementability, based on the possibility of using carriers with practically feasible maneuverability and the ability to stably estimate all state coordinates involved in the guidance method within the constraints imposed on the range of coordinates to be served and the value of control signals;
- the effective withdrawal of the carrier and information support systems from stability loss bounds, which predetermines the need to form guidance laws with the nonlinear (cubic) dependence on control errors [14, 22];
- consideration of the measured disturbances without augmenting the state vector;
- the possibility of forming the guidance method under an unknown interception time;
- universality, which characterizes the ability of the interception system to operate in a wide field of application conditions, including their non-compliance with the models underlying the design;
- the relative simplicity of control law formation within the implementable requirements to the computational performance of on-board computers;
- the possibility of information support of designed guidance methods.

4. CONCLUSIONS

In a series of future papers, we will discuss the possibilities of different approaches to optimizing guidance methods to HSA based on:

- the mathematical apparatus of the statistical theory of optimal control when minimizing quadratic and quadratic–biquadratic performance functionals;
- the concept of the inverse dynamics problems;
- gradient search;
- intelligent control.

Within the statistical theory of optimal control, we will consider approaches to designing a guidance method to HAS based on:

- the classical optimal control design scheme in the Letov–Kalman formulation [10, 15, 19–21];
- the local optimization scheme with a transformation of input signals affecting a given carrier type;
- the guidance law scheme with predicting the target position for a time interval determined by the interceptor's inertia;
- consideration of the mismatch between the dynamic properties of the target and the interceptor directly in the guidance law;
- minimization of local quadratic–biquadratic performance functionals [14, 22].

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