Model for Intercepting Targets by the Unmanned Aerial Vehicle

D. N. Kritsky(✉), V. M. Ovsiannik, O. K. Pogudina, V. V. Shevel, and E. A. Druzhinin

National Aerospace University "KhAI", Chkalova 17, Kharkiv 61070, Ukraine
d.krickiy@khai.edu

Abstract. The system for simulating flight control according to the characteristics of the unmanned aerial vehicle (UAV), as well as the flight paths of the UAV target, is proposed. The overview of the search for the optimal route for the UAV methods is performed. The following tasks were solved: development of the simulation model of the flight of a drone-target and an intercept drone; development of the subsystem of constructing the flight trajectory of the drone-target and building the optimal trajectory of the drone-interceptor; demonstration of the process of intercepting the goal by an intercept drone in real and virtual time, considering its geometric and aerodynamic characteristics.

Keywords: Unmanned aerial vehicles · Drone-interceptor · Drone-target · Optimal trajectory

1 Introduction

Recently, UAV are increasingly replacing standard manned aircraft from various fields of combat use of aircraft, due to a number of conditions [1]: higher survivability of the UAV (due to its lower visibility in the radar, infrared, optical and acoustic ranges); the longest flight duration is calculated around the clock today; less likely to be detected and destroyed by enemy antiaircraft defenses, compared to manned aircraft; the ability to carry out controlled safe flight at extremely low altitudes, sometimes even inaccessible to manned aircraft; the possibility of standing a high alert (operational) readiness for almost an unlimited time, as well as a significantly lower cost of development, mass production and military operation of the UAV and the training of operators of the ground or other command posts (CP).

Modern professional and semi-professional UAV are equipped with various kinds of cameras on board, conduct air patrols along the pipelines, calculate the area of ignition during fires, and have an environmental monitoring [2]. Currently, this set of tasks requires less time to perform, fewer forces, and it is also safe to say that in the future UAV will be used on an ever-larger scale.

One of the advantages that UAV have compared with a manned aircraft is the independence of the maximum flight time from the physiological capabilities of the flight crew. This is a significant advantage in the context of operational and strategic requirements in commensurate with the concepts of "Global strike" and "Global

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sustainable strike" [2]. As an example of the influence of the flight duration factor, can be considered this situation. For a hypothetical combat area measuring 192 × 192 miles, assuming the above requirement, there must be attack aircraft carrying weapons within 32 miles of any point in the area (five-minute time response for guaranteed destruction of mobile targets), which requires continuous presence in the area at least nine carriers defeat. To this should be added the conditions of basing restrictions, from land or sea bases, with a typical distance of about 1500 miles from the center of the combat area [3].

The key problem in the UAV design is the search for structural compromises between the dimensions of the UAV, combat survival, the size of the ammunition, cost, which determines the number of groups in conditions of limited assignations. The upper level of flight duration from the Global Hawk UAV experience, considering scientific and technological progress, can be several times higher than the level reached in 36 h for this UAV [4].

It should be noted that for combat UAVs, the required duration of stay in the combat area should be determined considering the intensity of spending weapons, ammunition on board, and the levels of its survival. The optimal ratio of fuel reserves and weapons ammunition depends on the predicted conditions of combat use - the intensity of hostilities, and various technical solutions can be used in the process of mission for its operational management, for example, having a modular weapon compartment with the ability to place both fuel and weapons [5].

Cost is a significant limitation on the dimension of the UAV. For conditions of the co-use with manned strike aircraft, the specified UAV accounting parameters, including cost, survival and combat effectiveness, should be determined by complex performance indicators with the search for the optimal composition of the aviation group with manned and unmanned strike systems, and the rational distribution of the share of combat missions between them [6].

The most obvious and effective way to counter the UAV is to identify such equipment with subsequent destruction. To solve this problem can be used as existing samples of military equipment, modified accordingly, as well as new systems [7].

One of the main issues in the destruction of enemy equipment is its identification, followed by maintenance. Modern types of anti-aircraft weapons systems of most types include radar warning station with various characteristics. The probability of detecting an air target depends on some parameters, primarily on its radar cross-section (RCS). Comparatively large UAVs are distinguished by greater RCS, which facilitates their detection. In case of compact devices, including those that was built with extensive use of plastics, the RCS decreases, and the task of detection is seriously complicated [8].

However, during creating promising air defense tools, measures are taken to improve the detection efficiency of targets. This development leads to the expansion of the RCS ranges and target velocities at which it can be detected and taken for tracking [9]. After identifying a potentially dangerous target, it should be identified and determine which object entered the airspace [10]. The correct solution of such a task will make it possible to determine the need for an attack, as well as to establish the characteristics of the target necessary for choosing the right weapon. In some cases, the correct choice of means of destruction can be associated not only with the extra consumption of inappropriate ammunition, but also with the negative consequences of a tactical nature. After successful detection and recognition of enemy equipment, the air defense system must carry out the attack and destroy it. For this should be used weapons that match the type of target detected. For example, large UAVs for recon or attack purposes should be hit with anti-aircraft missiles. In the case of low-altitude and low-speed light-class vehicles, it makes sense to use stem armament with appropriate ammunition. In particular, artillery systems with controlled remote detonation have great potential in the fight against UAVs [4].

The purpose of this publication is to develop algorithms and models of an UAV.

2 Interceptor Flight Path Formation Algorithm

The flowchart (Fig. 1) and method of interceptor flight path formation algorithm were developed.

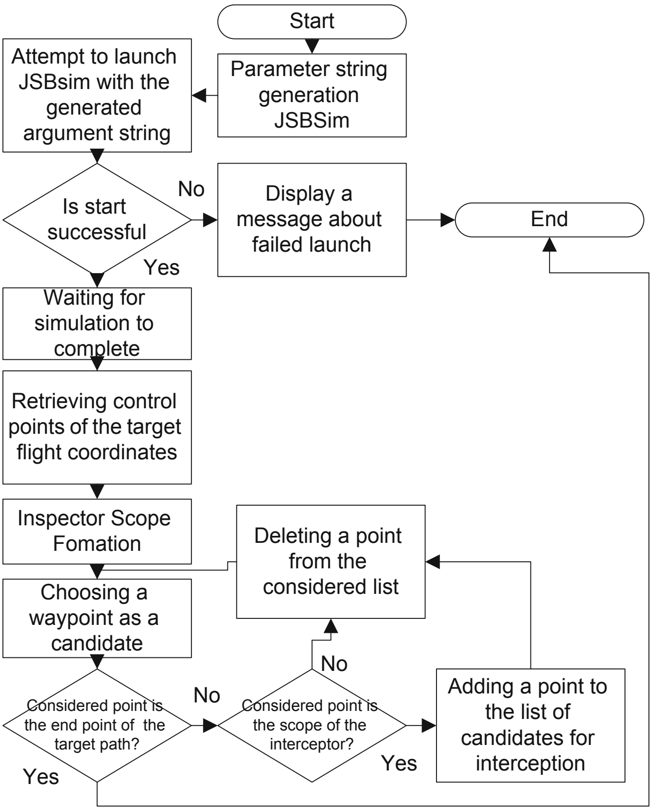


Fig. 1. The algorithm for determining the points of contact with the target

In the process of determining the trajectory of the interceptor, a guidance method using the "chase curve" principle was applied. This method was chosen because of its relatively simple implementation, as well as because of the possibility of using it when working not only in the guidance system of self-guided missiles, but also with UAV [11].

The method of pointing along a chase curve resembles the pursuit of a dog after a hare, therefore another name of this method can be found in the literature - pointing along a chasing curve or "dog curve" [12].

In this method, two possible cases should be considered: the achievement of a goal that is moving away (when passing courses, Fig. 2a) and the achievement of a goal that approaches (Fig. 2b).

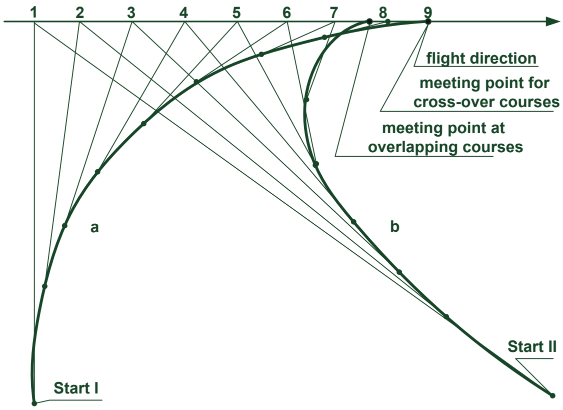


Fig. 2. Curves pursuing for passing-intersecting and counter-intersecting courses

In the first case (Fig. 2a), if the aircraft has a sufficient range and speed greater than the speed of the target, it can hit the target.

In the second case (Fig. 2b), as the aircraft approaches the target, the speed of rotation sharply increases. Such a load is not able to withstand the rocket body, and, in this case, it would simply break. But in reality, the control force created by the rudder can only grow to a certain value. Consequently, there may come a time when the steering wheel of the aircraft deviates to the stop, but the value that arises from this maximum control force will be insufficient for the necessary change of the direction.

From this point on, the aircraft will begin to move in a circle of minimum radius, which corresponds to the limiting control force. Guidance will stop, as the aircraft will not have time to develop on the target. After some time, the goal will leave the field of the coordinator's view, after which the guidance becomes impossible [12].

To derive the equation of the line, choose a coordinate system in which the abscissa axis passes through the initial position of the points P and A, the point A is at the origin of the xAy coordinate system. The ratio of constant velocities of points is denoted by k.

If we assume that for an infinitely small period of time the point P has covered the distance dS, and the point A - distance dS_1, then, according to the above condition, we obtain the relation $dS = k\ dS_1$, or

$$\sqrt{dx^2 + dy^2} = k\sqrt{d\xi^2 + d\eta^2},$$

Further it is necessary to express $d\xi$ and $d\eta$ through x, y and their differentials. Provided, the coordinates of the point P must satisfy the equation of the tangent to the desired curve, that is, $\eta - y = \frac{dy}{dx}(\xi - x)$.

Adding to this equation the equation $F(\xi, \eta)$ for the "evader" motion path specified by the condition, can be determined from the resulting system of equations ξ and η. After substitution of these values into the differential equation, it will be written as

$$\Phi\left(x, y, \frac{dy}{dx}, \frac{d^2y}{dx^2}\right) = 0.$$

Integration constants can be found from initial conditions ($y = 0; y' = 0$ when $x = 0$).

In the general case, for an arbitrarily given curve $F(\xi, \eta)$, it is rather difficult to find a solution to the resulting equation. The task is greatly simplified if we consider the simple case when the trajectory of the "evader" is straight.

Consider the case of A_0 (0, 0), P_0(0, 1) when the "evader" moves along the x axis and when $k > 0$. At any given time, the "evader" is always on a tangent to the curve of the "pursuer's" motion path, so $\frac{dy}{dx} = \frac{-y}{a-x}$.

Based on what let's write the differential equation $y + y'(a - x) = 0$, where $y > 0$.

From the condition $a = V \bullet t$ floats $\frac{y}{y'} + Vt = x$, after differentiation by time $\dot{y} = y' \bullet \dot{x}$ and $\dot{y}' = y'' \bullet \dot{x}$, on the basis of which find out $\dot{x} = \frac{dx}{dt} = \frac{V \cdot y'^2}{y \cdot y''}$

Let's write the expression to determine the length of the curve

$$1 = Wt = k\int_0^x \sqrt{1 + (y')^2}dx$$

From the expressions $dx^2 + dy^2 = W^2dt^2$ and $w^2 = \frac{dx^2}{dt^2} + \frac{dy^2}{dt^2} = \dot{x}^2 + (y' \cdot \dot{x})^2$ leaks out $\dot{x} = \frac{w}{\sqrt{1 + y'^2}}$

Similarly, differentiation by y carried out $y'' - k \cdot \frac{y'^2}{y} \times \sqrt{1 + y'^2} = 0$

Substitution Solution $u = x' = \frac{1}{y'}, y'' = \frac{-1}{u^3}\frac{du}{dx}$, with separation of variables leads to $\frac{-du}{\sqrt{1 + u^2}} = k \cdot \frac{dy}{y}$ after integration we get $\operatorname{arsinh} u = k \cdot \ln y + C$.

Further, after using the formal definition sinh with $C_1 = e^C$, we obtain $x' = \frac{dx}{dy} = \frac{1}{2}\left[(C_1 \cdot y)^k - (C_1 \cdot y)^{-k}\right]$

Integrate once again with the definition of continuous integration C_2. From the initial conditions $\left.\frac{dx}{dy}\right|_{y=1} = 0$ leaks out $C_1 = 1$, and also $x|_{y=1} = 0$ the result is

$$C_2 = \frac{k}{1-k^2} \text{ or } x(y) = \frac{1}{2}\left(\frac{y^{(1+k)}}{(1+k)} - \left\{\begin{matrix} \frac{y^{(1-k)}}{(1-k)} \\ \ln|y| \end{matrix}\right\}\right) + \left\{\begin{matrix} \frac{k}{(1-k^2)} \\ -1/4 \end{matrix}\right\}\left\{\begin{matrix} k \neq 1 \\ k = 1 \end{matrix}\right.$$

Based on these equations it was possible to obtain the equations that were given above.

3 Software Architecture

"InterceptionUAVSimulation" software system is a software system that consists of a user interface module—an interface implemented using the XAML markup language. It integrates the JSBSim flight dynamics modeling system, the WPF. Media animated data modeling system, the XSeed data visualization module, and the UAV flight path design module, implemented as a set of classes written in C #, into a single complex. This set of modules and subsystems together constitute a single system for solving the problem of designing and developing simulation models of a UAV target along a given route, taking into account the relief and the UAV interceptor, based on tactical and technical characteristics of the target and its trajectory.

Figure 3 show the general file architecture of the "InterceptionUAVSimulation system".

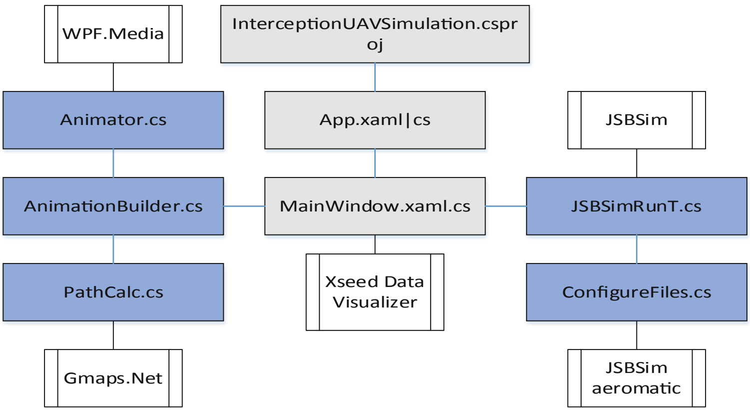


Fig. 3. Software file structure

The darker color in Fig. 3 shows files that contain the main logic classes of the software system that perform certain tasks in the simulation process. Description of the main modules of the system used to achieve the objectives of this work is in below.

The Animator.cs file is a class containing the logic for designing animated GUI objects of software. The main purpose of this module is the formation of graphical representations of the target interception model of the drone.

The PathCalc.cs file contains a class that implements the logic for conducting geolocation calculations and scaling UAV flight routes. There are temporary calculations of UAV flight routes, scaling the speed of the animated model during the demonstration.

The AnimationBuilder.cs file describes a class that contains the logic of matching data obtained during the operation of the Animation and PathCalc modules, after which the final animated model is designed and provided to the system for its further demonstration to the user.

The ConfigureFiles.cs file contains class definitions that contain the logic for designing UAV configuration files, creating their XML markup, creating the directory structure, that a necessary for the correct operation of the JSBSim system during flight simulation.

The JSBSimRunT.cs file describes the main class for working with the JSBSim system. This class is used to build queries to the JSBSim system, to verify the correctness of the file structure of the UAV configuration. This module also implements a system for notifying the user about errors in the system in case of inconsistencies in the location of configuration files UAV representation.

After processing the received data, the XSeed subsystem provides InterceptionUAVSimulation with a set of graphical representations of the UAV telemetry readings during the flight. In turn, GMaps.Net, on the basis of the data obtained, forms a set of interface elements for visualizing the flight process, after which it transfers them to WPF.Media to create an animated representation of the flight process of the UAV.

4 Deploying the Software System

In the main window of the program, the user needs to fill in information about the main design features of the UAV target, such as wing area, fuselage length, maximum lifting weight, relative coordinates of the center of gravity, relative coordinates of the point of view that are needed to visualize the flight of the aircraft, the location and number of engines, the area of horizontal and vertical tail, as well as the name of the projected aircraft. In addition to the basic characteristics of the aircraft, user must enter the characteristics of the engine installed on the aircraft.

Next, the user goes to the window of registration files configuration UAV interceptor. After filling in the configuration files of the target and the interceptor, a transition takes place to the map operation window (Fig. 4).

On this form, the user must specify the targets and coordinates of the location of the launch point of the interceptor using double clicks on the map of control points of the proposed route. Switching between the target route setting modes and the interceptor launch point is performed using the appropriate controls. If an error occurs during the task of markers on the map, it is possible to reset the current location of the markers by clicking on the “Clear target route” button.

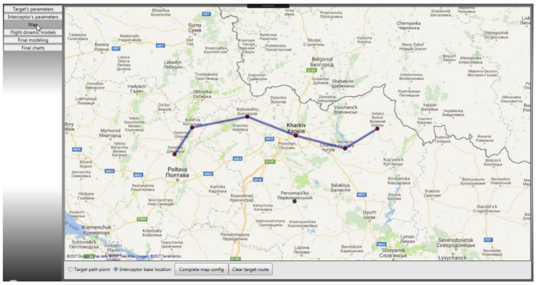


Fig. 4. Map processing form after completing route planning

After completing the map layout (Fig. 4), click the “Complete map config” button, after which the system will launch the flight scenario design module for the target.

After the map layout has been completed and the flight script file has been designed, a transition is made to the launch form of the design of a simulation flight model of the target and interceptor (Fig. 5). On this form, the user can see the directories in which the configuration files of the UAV-target and the interceptor are located, in case of extreme need open them to make changes.

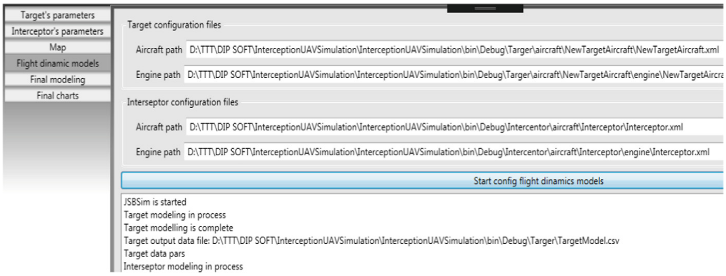


Fig. 5. JSBSim system after successful completion of the simulation

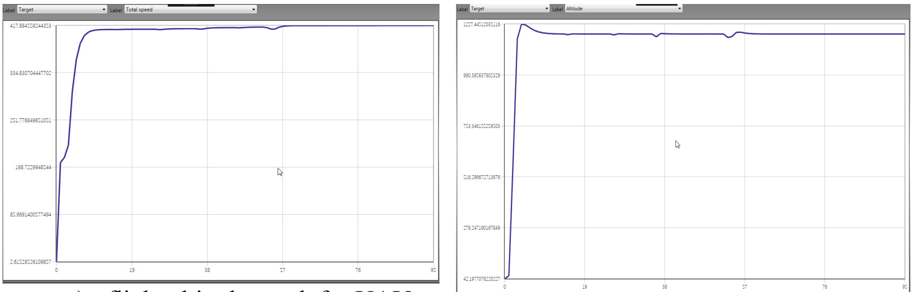
Also on this form there is a logging area, in which messages about events that have arisen in the course of aircraft simulation are displayed. After reviewing the received configuration files, user should click the “Start config flight dynamic models” button, after which the JSBSim system will be launched alternately for the target and the interceptor.

In the intervals between JSBSim launches, the system will analyze and extract the geolocation data of the target during the flight. This data set is used by the system to calculate the interceptor’s flight path as calculated by the homing method along the pursuit curve.

Upon successful completion of the simulation, a corresponding message will be displayed in the logging area (Fig. 5) and a flight report file will be created on the disk for the target and the interceptor.

After the simulation of the interception process is completed, data is read from the target and interceptor files, parsed for further visualization using an animated model and graphical reports, and the transition to the form demonstrating the process of intercepting the target. First, on this form, in the map location area, the obtained flight trajectories are shown. In the lower part of the form, there are controls for the playback speed of the animation model and the start/pause of the demonstration. In the process of modeling, the user is provided with a simplified visual process of pursuing, neutralizing and returning to the interceptor base. The interceptor is marked in red on the form, and the target is in green. During the demonstration, the user is given the opportunity to zoom in time using the control element in the lower left area of the form, by default, the visualization takes place in real time. After neutralization, the target is painted black, the rendering stops and a message about the success of the interception process is displayed, after which the interceptor starts to return to the launch base.

When switching to the form of graphical reports (Fig. 6), the user can view the metric readings obtained during the simulation by selecting the appropriate indicator and its membership (goal or interceptor).



a) flight altitude graph for UAV target

b) graph of the speed of flight of the UAV-goal

Fig. 6. Graphical reports

5 Conclusions

In the course of the project, the task of designing and developing a simulation model of the process of interception of the UAV-target by the UAV-interceptor was solved.

First, the analysis of the subject area was carried out, various systems and methods of countering the UAV were considered, possible ways of neutralizing the UAV were studied. Further, the decomposition of the project tasks into subtasks was performed and algorithms for solving these subtasks were compiled.

Analyzing the velocity plots, as well as the results of modeling the construction of trajectories for target intercepting, we can conclude that the developed algorithm allows us to construct an intercept trajectory in such a way that the interception process itself is carried out in the shortest possible time.

Next, a software system was created that builds the flight path of the target, calculates the flight path of the target, calculates the interceptor's flight curve using the chase curve method, and also built an animated model of the target interception process.

The developed system uses the JSBSim flight dynamics simulation program, the XSeed graphic report generation module that is used in the process of generating graphs of changing UAV characteristics during the flight, the geographic points targeting subsystem on the world map GMaps.Net, as well as the main software product WPF application that connects the entire set of modules into a single system.

The developed software system will help researchers and developers of UAVs to determine the optimal geometric and aerodynamic parameters of the aircraft, necessary to achieve the goals and objectives, as well as to determine the possible trajectory of interception of the target.

The practical value of the obtained results is that the work, that have been done, will help in the development of algorithms for automatic control of the UAV-interceptor.

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