DEVELOPMENT OF HIGH SPEED FLYING VEHICLE ON-BOARD INTEGRATED NAVIGATION, CONTROL AND GUIDANCE SYSTEM

M.N. Krasilshchikov*, D.A. Kozorez*, K.I. Sypalo**
***Moscow Aviation Institute (National Research University), Russian Federation**
***Central Aerohydrodynamic Institute, Russian Federation**

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Abstract

This presentation is dedicated to actual problem of architecture, algorithms and hardware of on-board integrated navigation, control and guidance system development for high speed vehicle (HSV) with significant lift-drag ratio (K>3), considering wide set of uncontrollable factors, such as deterministic, stochastic and fuzzy ones: thrust and aerodynamics properties uncertainty, wind, atmosphere density, navigation and control errors stochastic performances. Considered HSV is equipped by hypersonic scramjet and, therefore, the trajectory of such vehicle includes various sections, such as launching section implemented by rocket buster, cruise section by scramjet utilization and passive atmospheric aeroballistic terminal section.

1 Problem statement

The main HSV control problem consists in providing of high accurate terminal control in order to guide HSV into prescribed point of 3D space with terminal 3D miss not more than 1 meter (RMS) on each axis. Besides, there are restrictions on terminal point approaching conditions. Namely, both path and heading angles of approaching trajectory should met specific restriction as well as considering technical restriction on terminal velocity and control [1].

The HSV control problem mentioned above should be solved, considering specific HSV performances as controlled object, namely:

- there are uncontrollable stochastic and uncertain factors (atmosphere density, thrust and aerodynamics variations, wind, etc);
- low aerodynamic control efficiency;
- significant delay (10-15 sec.) between attitude and mass center controlled motions;
- significant HSV velocity head changing.

Considering all above said let's involve so called systematic criteria, which could be interpreted as probability of HSV mission success at the terminal time instant T:

$$P\left\{\begin{matrix} |x_C(T)-x_{tp}|\le\varepsilon_X, |z_C(T)-z_{tp}|\le\varepsilon_Z, \\ |h(T)-h_t|\le\varepsilon_h, \Theta_{\min}\le\Theta(T)\le\Theta_{\max}, \\ \Psi_{\min}\le\Psi(T)\le\Psi_{\max}, V(T)\ge V_{\min} \end{matrix}\right\} > P_{pre} \quad (1)$$

where

P_{pre} is prescribed probability value, which correspond to HSV mission success;

x_{tp}, z_{tp} are coordinates of prescribed terminal point 2D position;

$x_C(T)$, $z_C(T)$ is 2D HSV mass center position at the terminal time instant T;

$h(T)$, h_t are HSV mass center and terminal point of space altitude correspondingly at the terminal time instant T;

$\Theta(T)$ is HSV trajectory path angle at the terminal time instant T;

$[\Theta_{\min}, \Theta_{\max}]$ is HSV path angle restriction;

$\Psi(T)$ is HSV heading angle at the terminal time instant T;

$[\Psi_{min}, \Psi_{max}]$ is HSV heading angle restriction;

$V(T), V_{min}$ are HSV velocity and velocity prescribed value correspondingly at the terminal time instant T;

$\varepsilon_x, \varepsilon_z, \varepsilon_h$ are maximal values of HSV terminal miss on 2D position and altitude correspondingly.

2 Principles of problem solution

To solve discussed HSV control problem it is necessary to define the following:

- on-board integrated navigation, control and guidance system architecture;
- on-board hardware set;
- on-board navigation, control and guidance algorithms.

All above listed positions should be defined in order to provide the requirements, set by criteria (1).

The following basing principles have been used by discussed problem solution:

- The various on-board integrated system architectures have been generated applying to cruise and terminal section of HSV flight.
- The navigation and control systems have been synthesized separately basing on Kalman-Bucy theorem.
- Navigation problem solution includes specific procedures for uncertain parameters identification.
- Procedures of both on-board integrated system architecture and algorithms generation are started from terminal section of flight.

Figure 1 illustrates these principles and procedures. So, according Fig.1, the following actions are utilized to implement given above principles:

- The normal program trajectory at the terminal section of HSV flight numerically generated basing on prior data concerning terminal point position and all above listed restrictions and requirements. Both attack and roll angles are considered as control actions, which it is equivalent of required lateral acceleration load value. It is supposed, that left end-point of trajectory is fixed and belongs to absorption area. Simultaneously both trajectory path and heading angles are defined.
- The absorption area is generated applying to normal program trajectory, computed accordingly to p.1 above, i.e. restrictions on HSV state vector are defined at the cruise section of flight terminal time instant.
- The guidance algorithm generated, which provides HSV guidance in the vicinity of the generated program normal trajectory. The attitude control algorithm is generated in order to compensate instant terminal miss, predicted by on-board navigation system.
- The navigation algorithm is generated in order to provide necessary accuracy of both guidance and attitude control.
- Both reference and on-line renewed normal trajectories generated at the cruise section of flight applying to absorption area, defined by p.4 above. Besides, requirements to launching area at the cruise section of flight left end are defined.
- The on-line renewed normal trajectory generated applying to cruise section of flight in order to compensate uncontrollable factors influence in the vicinity of the reference trajectory.
- Both navigation and identification algorithms are generated applying to cruise section of flight, considering computed absorption area and control algorithms. Simultaneously is defined both hardware and hardware requirements sets applying to cruise section of flight.

As it is clear from all above said, the terminal section of flight is key one, because here is implemented high accurate guidance on terminal point of space, utilizing multi spectral hardware, providing “target point” tracking.

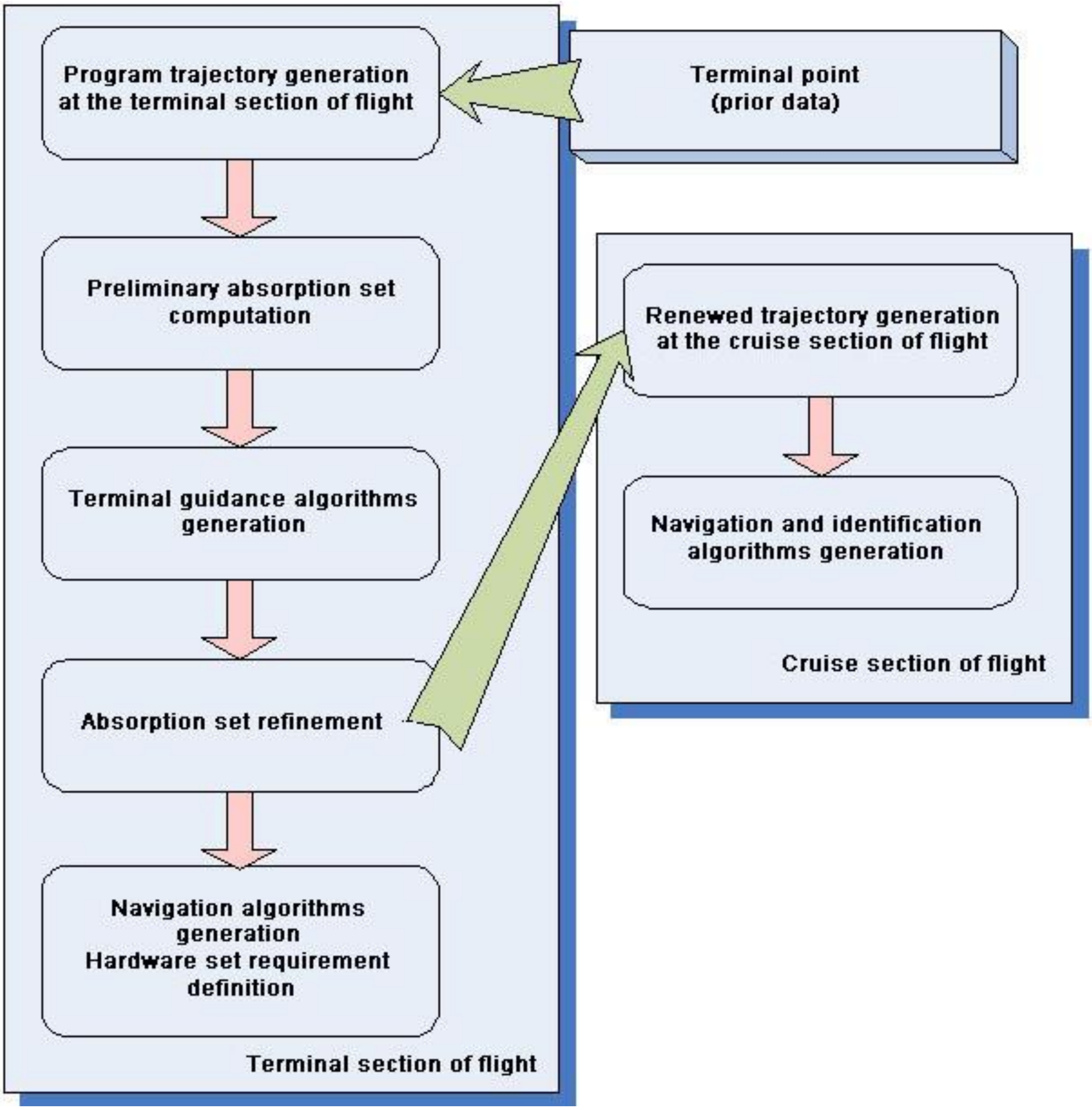

Fig. 1. Procedure of on-board integrated navigation, control and guidance system development

The corresponding architecture of on-board integrated system applying to terminal section of flight is represented on Figure 2.

As one can see, the following components of on-board integrated navigation and control system can be emphasized:

- on-board hardware, which includes inertial sensors, radio altimeter, onboard radar, operating with synthesized aperture, considering onboard digital map;
- on-board algorithms providing navigation, guidance and both mass center and attitude control;
- actuators, which generating control forces and torques.

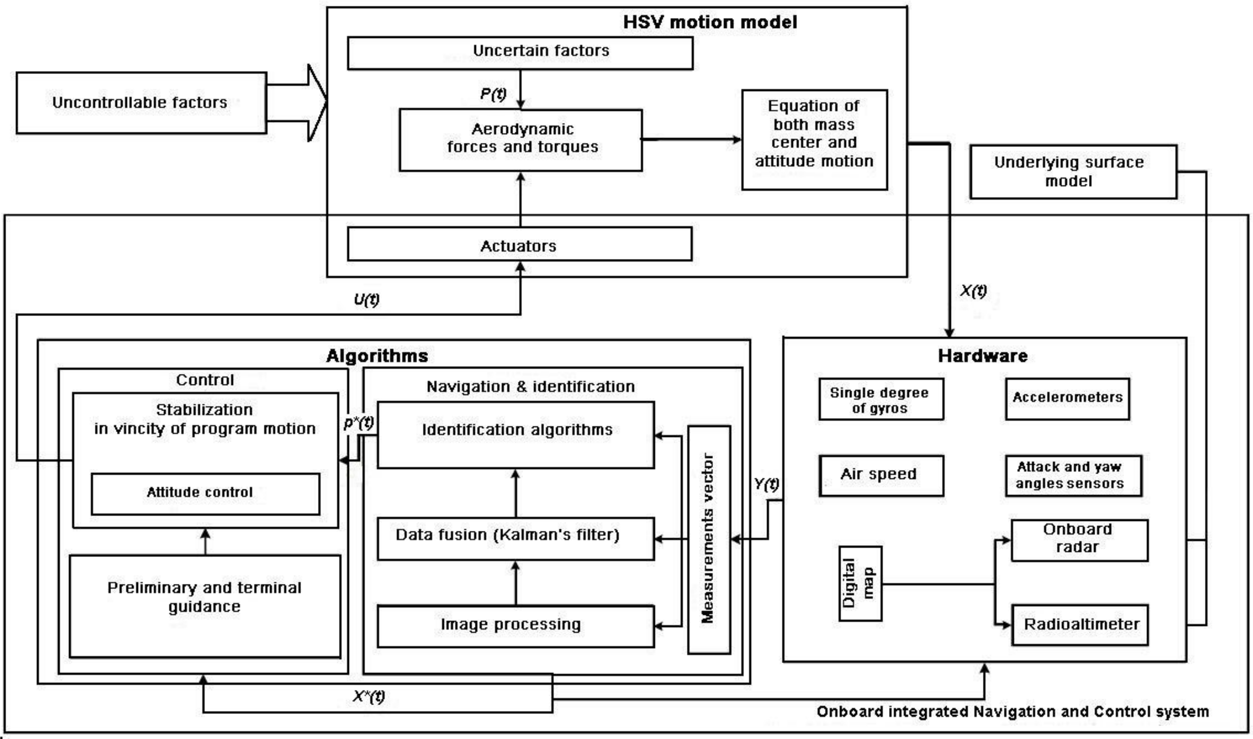

Fig. 2. Architecture of on-board integrated system

The following admissions are used later on by on-board integrated system algorithms generation:

- control problem is considered as complete data one, considering the fact, that navigation problem is already solved;
- attitude control problem is also already solved in order to provide needed level of vehicle stability, fast acting, etc;
- it is supposed that by absence of uncontrollable factors are normal trajectories, providing required terminal guidance accuracy, considering all existing restrictions and requirements;
- it is supposed also, that control resource is sufficient to compensate influence of uncontrollable factors in order to provide terminal accuracy requirements and phase vector components restrictions.

As the result, discussed problem solution will include solution of the following two problems [1]:

- Normal program trajectory generation, supposing complete information about HSV state vector. Solution of this problem includes both program control and corresponding normal trajectory considering all restrictions and requirements.
- Homing problem in vicinity of the generated normal program trajectory. Solution of this problem includes guidance trajectory, providing instant terminal miss compensation, considering influence uncontrollable factors and uncertainties.

3 Terminal guidance

Solution of the first problem is provided by numerical variation algorithm which maximizes terminal HSV velocity, considering restrictions on control, 2D terminal miss and line incidence position.

This numerical algorithm includes also the procedure of absorption area (i.e. area of space, providing HSV leading to terminal point considering restrictions on approaching conditions) computation. The algorithm discussed generates normal program trajectories using 4-5 iterations. Standard forms of such trajectories are given by Figure 3.

Solution of the second problem consists in control actions generation according to guidance law, using estimations of deviations of actual

HSV state from required ones. The concept of utilizing homing algorithms consists in periodical generation of renewed normal guidance trajectory, using actual estimation of HSV state [2]. These estimations are output of control observation system.

The renewing of normal guidance trajectory is performed considering all above listed restrictions at the terminal time instant (Figure 4).

In other words, the following requirement should meet at the right endpoint of the renewing trajectory:

$$L_p(T) = L_{tp},\ h_p(T) = h_{tp},\ B_p(T) = 0,\\ \Theta_p(T) = \Theta_{tp},\ \Psi_p(T) = \Psi_{tp} \tag{2}$$

where index p is referred to renewing normal trajectory, $L_p(T)$ is longitudinal position HSV (distance to the target point), $h_p(T)$ is HSV altitude at the terminal time instant, $B_p(T)$ is lateral HSV deviation at the terminal time of instant, $\Theta_p(T)$ and $\Psi_p(T)$ are path and heading angles correspondingly at the terminal time instant.

The analytical form of renewed guidance trajectory is used in order to perform renewing procedure on-line. For this one uses Bezier curves. As the result, it is possible to find both trajectory and control in analytical form. So, longitudinal and lateral control actions are correspondingly:

$$\alpha_{com} = \frac{1}{C_y^{\alpha}}\left(\frac{2}{\rho V^2 S} Y_{com} - C_y^0 - C_y^{\delta}\delta\right) = \\ \frac{1}{C_y^{\alpha}}\left(\frac{2}{\rho V^2 S}\frac{-\dot{\Psi}_{com}\cos\Theta}{\cos(\gamma_{com})} - C_y^0 - C_y^{\delta}\delta\right), \tag{3}$$

$$\gamma_{com} = arctg\left(\frac{-\dot{\Psi}_{com}\cos\Theta}{\left(\dot{\Theta}_{com} + \frac{g}{V}\cos\Theta - \frac{V}{r}\cos\Theta\right)}\right). \tag{4}$$

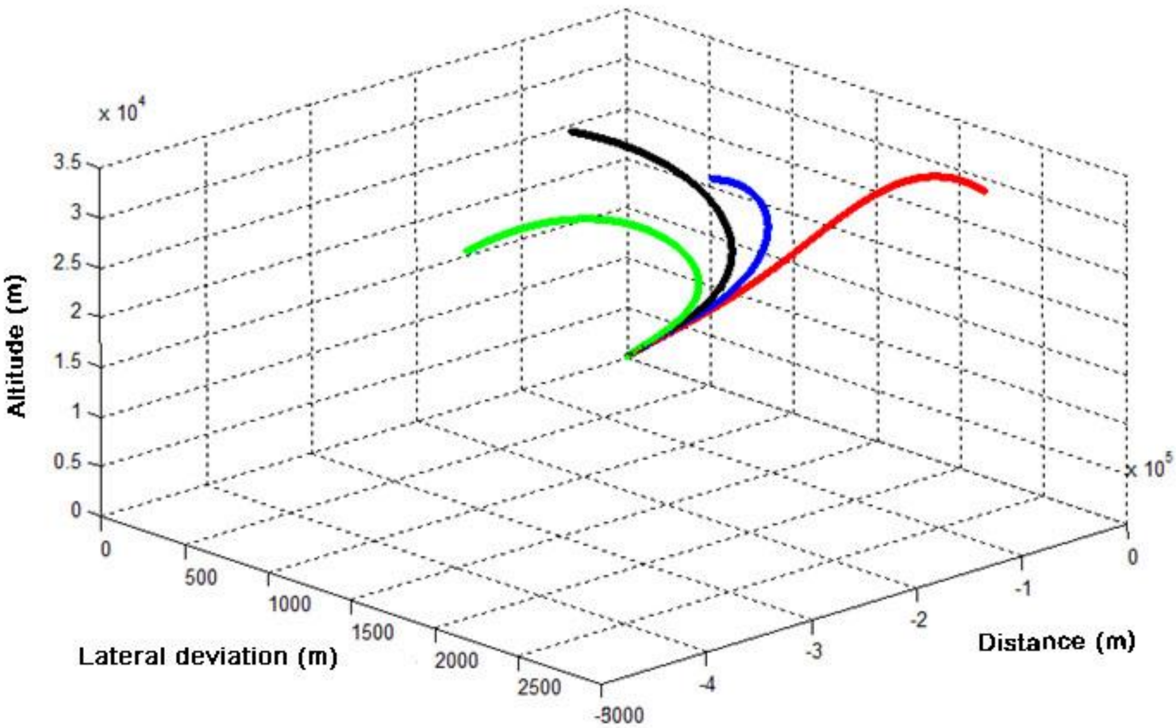

Fig. 3. Standard forms of normal program trajectories

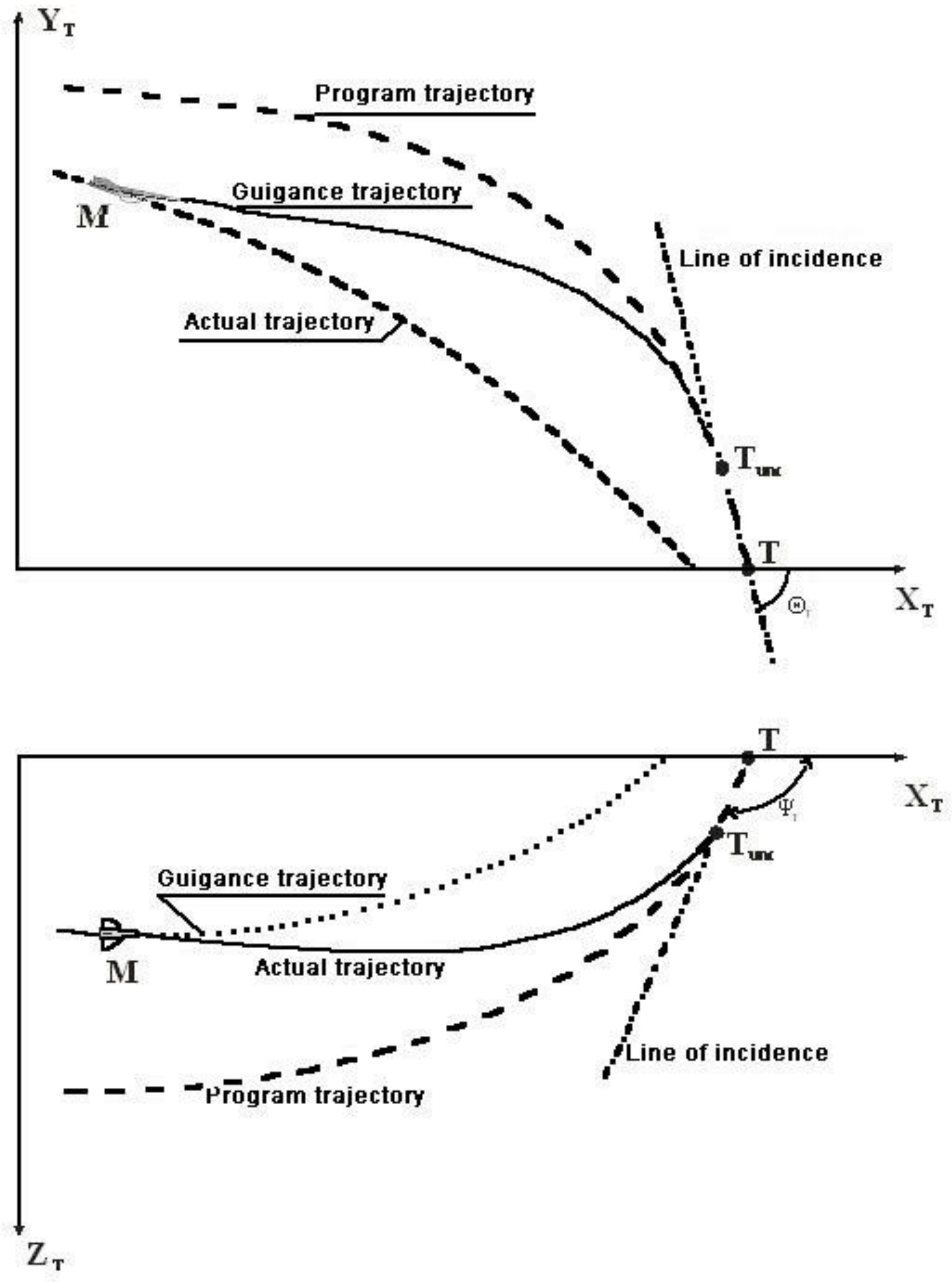

Fig. 4. HSV trajectories at terminal section of flight

Mathematical simulation of renewing trajectories generation demonstrates the following additional restrictions:

- Algorithm based on splines or Bezier curves of the 3-rd order cannot be used for longitudinal control generation, if terminal path angle is more than 600.
- Algorithm based on Bezier curves of the 2-nd order cannot be used for lateral control generation, if initial and terminal heading angles have different signs.

4 Problem solution on cruise section

It is necessary to underline here that scramjet thrust value at the cruise section of flight significantly depends on both HSV flight mode and attitude as well as on control restrictions. The following procedure gives an opportunity to consider all above mention scramjet specific features [3]:

- The network of program trajectories is generated, which are considered later on as reference ones. These trajectories generated in order to minimize the control resource, namely: the reference trajectory provides HSV mass center transfer with fixed path angle from initial arbitrary point of initial absorption area into absorption area point with prescribed altitude, M number and path angle.
- The networks of program trajectories are generated, considering HSV mass and absorption areas variations.
- Renewed normal trajectories on-line are generated, which are correspond to initial HSV state, obtained from onboard navigation system. As the result, are defined the following data: required program control as required both attack and path angles as well as scramjet thrust.

Renewed trajectory generation is performed at the same way as program normal trajectory generation, but for renewed trajectory HSV actual state vector is used, obtained as on-board navigation data.

The standard program trajectory is given by Figure 5.

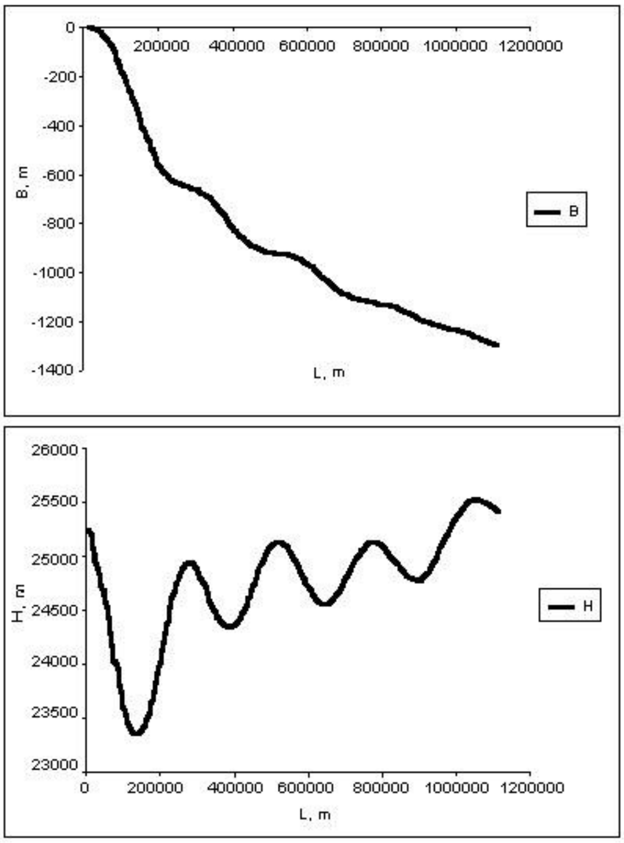

Fig. 5. Standard program trajectory

Architecture of on-board integrated navigation system applying to cruise section of flight is given by Figure 6.

This architecture is deeply integrated one. As hardware of system multichannel GNSS-receiver, inertial measurement unit, radio altimeter and on-board radar are utilized. Specific modification of extended Kalman's filter (so-called "scalar" modification) is used as data fusion algorithm. Simultaneously with this navigation algorithm operates identification algorithm, based on standard Kalman's filter, obtained due to linearization of corresponding equation in the vicinity of estimations, generated at the previous step of algorithm operation.

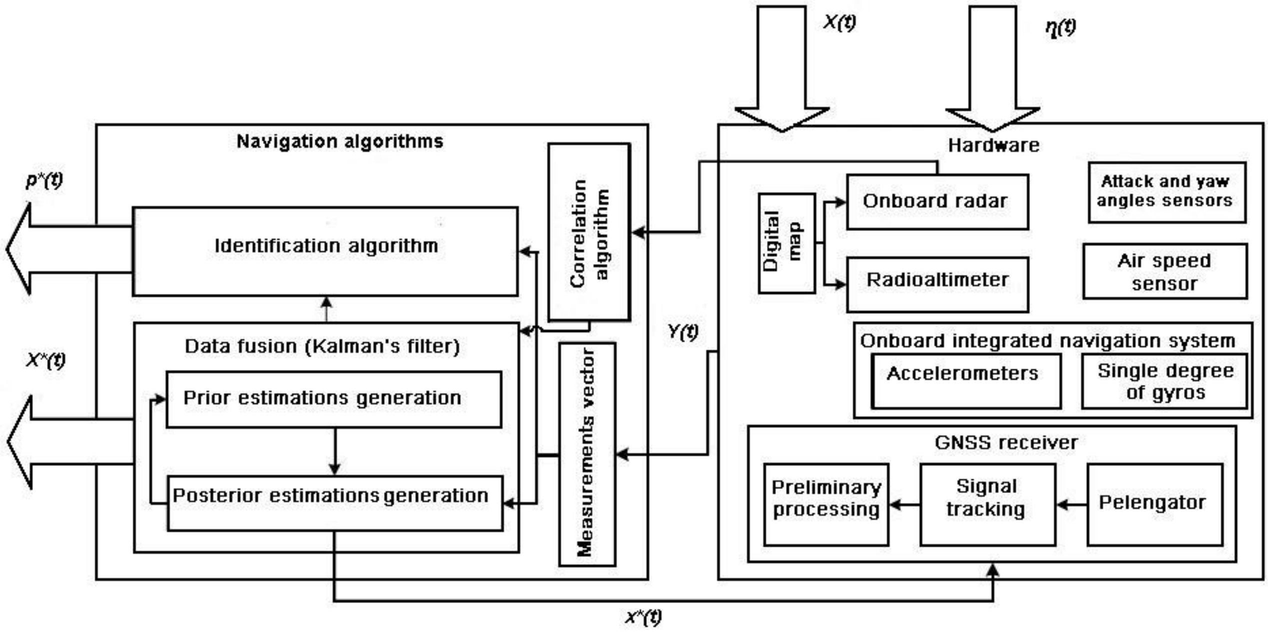

Fig. 6. Architecture of on-board integrated navigation system on cruise section

5 Results

The specific object-oriented software complex has been developed for mathematical simulation of all described above models, procedures and algorithms. As the result of simulation have been evaluated performances of HSV onboard integrated guidance, navigation and control system. In particular, integrated evaluations of terminal HSV guidance accuracy are given by Figure 7 as the result of Monte-Carlo procedure.

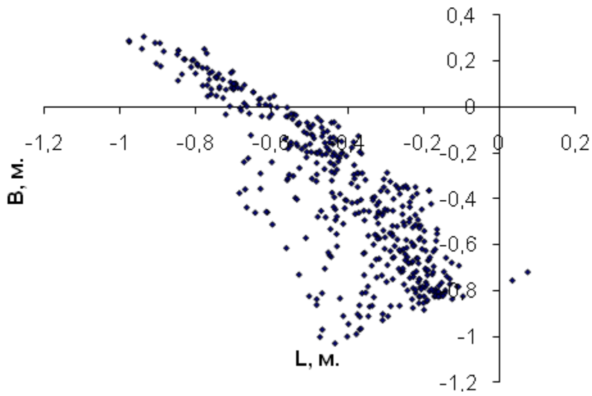

Fig. 7. HSV terminal guidance points area

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