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Conceptual Design of Navigation System for a Commercial Launch Vehicle

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ABSTRACT:- *In this study was considered a concept of integrated onboard navigation systems for commercial launch vehicles in the context of the current task, and provided mathematical models of its elements for different variants of designing structure and composition. Has been set and simulated the technical problem of the conceptual design of an integrated navigation system for the space launch vehicle qualified to inject small artificial Earth satellites into low and medium circular orbits with application of GPS technologies.*

Keywords:- Gimbaled inertial navigation system (GINS), onboard integrated control systems (OICS), global positioning system (GPS), inertial navigation system (INS), mathematical model (MM), launch vehicle (LV), navigation, pseudorange, pseudovelocity, launch vehicle, self-guided system (SGS), Kalman filter, control loop, control system (CS), trajectory, coordinate, orientation

I. INTRODUCTION

A key tendency in the development of affordable modern navigation systems is displayed by the use of integrated GPS/INS navigation systems consisting of a gimbaled inertial navigation system (GINS) and a multichannel GPS receiver [1]. The investigations show [2, 3], that such systems of navigation sensors with their relatively low cost are able to provide the required accuracy of navigation for a wide class of highly maneuverable objects, such as airplanes, helicopters, airborne precision-guided weapons, spacecraft, launch vehicles and recoverable orbital carriers.

The study of applications of GPS navigation technologies for highly dynamic objects ultimately comes to solving the following problems [4, 5]:

1. Creation of quality standards (optimality criteria) for solving the navigation task depending from the type of an object, its trajectory characteristics and restrictions on the weights, dimensions, costs, and reliability of the navigation system.
2. Choosing and justification of the system interconnecting the GPS-receiver and GINS: uncoupled, loosely coupled, tightly coupled (ultra-tightly coupled).
3. Making mathematical models (MM) of an object's motion, including models of external factors beyond control influencing object (disturbances). This requires to make two types of object models: the most detailed and complete one, which will be later included in the model of the environment when simulating the operation of an integrated system, and a so-called on-board model, which is much simpler and more compact than the former one, and which will be used in the future to solve the navigation problem being a part of the on-board software.
4. Making MM for GINS in consideration of use of gyroscopes and accelerometers (i.e. it is required to make a model for navigation measurements supplied by GINS, taking into account systematic (drift) and random measurement errors).
5. Making a model of the navigation field of GPS, including system architecture, a method of calculating ephemeris of navigation satellites in consideration of possible errors, clock drifts on board the navigation satellites, and taking into account conditions of geometric visibility of a navigation satellite on different parts of the trajectory of a highly dynamic object.
6. Making a model of a multichannel GPS receiver, including models of code measurements (pseudorange and pseudovelocity) and, if necessary, phase measurements, including the whole range of chance and indeterminate factors beyond control, existing when such measurements are conducted (such as multipath effect).
7. Choosing an algorithm to process measured data in an integrated system in agreement with the speed-of-response requirement (the possibility to process data in real time) and demanded accuracy in solving a navigation task.

8. Creating an object-oriented computer complex for the implementation of the above models and algorithms with the objective to model the process of functioning of the integrated navigation system of a highly dynamic object.

Let's consider the above objectives, having regard to peculiarities of the subject of inquiry, namely a commercial launch vehicle, designed to launch payloads into low Earth orbit (LEO) or geostationary orbit (GSO), in more details.

Within the framework of this study we shall consider a light launch vehicle which has been jointly developed by the European Space Agency (ESA) and the Italian Space Agency (ASI) since 1998 [6]. It is qualified to launch satellites ranging from 300 kg to 2000 kg into low circular polar orbits. As a rule, these are low cost projects conducted by research organizations and universities monitoring the Earth in scientific missions as well as spy satellites, scientific and amateur satellites. The launch vehicle Vega [7, 8, 9] is the prototype of the vehicle under development.

The planned payload to be delivered by the launch vehicle to a polar orbit at an altitude of ~700 km shall be 1500 kg [10]. The launch vehicle is tailored for missions to low Earth and Sun-synchronous orbits. During the first mission the light class launch vehicle is to launch the main payload, a satellite weighing 400 kg, to an altitude of 1450 km with an inclination of the orbit 71.50^0. Unlike most single-body launchers, this vehicle is to launch several spacecraft.

The launch vehicle under consideration is the smallest one developed by ESA. We assume that the new launch vehicle will be able to meet the demands of the market for launching small research satellites and will enable universities to conduct research in space. The launcher will be primarily used for satellites that monitor the Earth surface. The injection is conducted according to the most popular and simplest (and the cheapest) scenario [11, 12], more specifically: the instrument unit and the navigation system ride atop the 3rd stage of the launch vehicle. Thus, launching until separation of the 4th stage carrying payload is conducted in accordance with the data provided by the navigation system which estimates 12 components of the launcher state vector, including position, velocity, orientation angles and angular velocities. Basically, launching may be done upon implementation of any of the possible algorithms, for example, a terminal one, that provides accuracy of the 3rd stage launching to the calculated point of separation of the 4th stage or the traditional algorithm which minimizes the deviation of the center of mass of the launcher from the preselected programmed trajectory [7, 5, 10].

II. PROBLEM STATEMENT

From the standpoint of the problem concerned, namely the synthesis of the navigational algorithm of the space launcher in the proposed injection sequence we are interested only in the first factor, i.e. accuracy of lifting of the 3rd stage to the point of separation 4th stage. This accuracy, other conditions being equal, is determined by the precision of solving a navigation task in lifting the 3rd stage in consideration of both components: the center of mass and the velocity of the stage. They predetermine the required impulse for the 4th stage [13].

Thus, we may determine the main criterion of the accuracy of the navigation task in relation to the integrated inertial navigation system of the space launch vehicle: we need to ensure maximum accuracy in determining the position and velocity vectors of the 3rd stage of the launch vehicle in the exo-atmospheric phase of the mission in the selected for navigation coordinate system. Clearly, this accuracy, in its turn, other things being equal, depends upon the accuracy of the initial conditions of travel of the 3rd stage, or in other words, the accuracy of navigation on the previous atmospheric phase of the mission [1].

Consequently, in the case of the proposed injection sequence the simplest and most obvious criterion for evaluation of the accuracy of the synthesized system should be adopted. It is required to ensure maximum accuracy in determining the vectors of position and the center -of- mass velocity of the launcher during the flight of the1st-3rd stages, i.e. in atmospheric and exo-atmospheric phases of the mission. This accuracy can be characterized by the value of the dispersions posteriori of the corresponding components of the mentioned vectors [10, 14].

Now let's consider the possible integration schemes for GINS and GPS receiver with respect to this technical problem [15]. As it has been aforementioned, currently we can think of three possible integration schemes as follows [5, 16-20]:

- uncoupled (separated subsystems);
- loosely coupled;
- Tightly coupled (ultra-tightly coupled).

Let's consider the peculiarities of these systems.

Uncoupled systems are the simplest option for simultaneous use of INS and GPS receiver (Fig. 5.2) [5, 21]. Both systems operate independently. But, as INS errors constantly accumulate, it is necessary eventually to make correction of INS according to data provided by the GPS receiver. Creating such architecture requires minimal changes to the hardware and the software [15].

In loosely coupled systems GINS and GPS also generate separate solutions, but there is a binding unit in which GPS-based measurements and GINS readouts make assessment of the status vector and make corrections of data provided by GINS [5, 21].

The main factors that determine the structure and composition of the navigation system are required accuracy and reliability of navigation parameters within the given limits on the weight, size, power consumption (in some cases - for the time of the system development and operation security) (Table 1) [5, 10]. Besides, consideration should be given to:

- types of objects;
- cost of the complex;
- service conditions;
- possibility of maintenance and repair.

Table 1

The main advantages of integrated systems

Factors	**Quality characteristic**
Accuracy	substantially
Weight	decreasing by 30-70%
Volume	decreasing by 50-60%
Power consumption	decreasing by 25-50%
Reliability	increasing ≈ 2 times
Redundancy level	increasing by 50% and more
Cost	substantially

Proceeding from the above information we may conclude that an integrated navigation system of future launchers should have a structure which, depending on the function ability of SGS receiver, shall allow operating in accordance with the algorithms both as an uncoupled and tightly coupled system. It should be capable of processing coordinates and velocities as well as pseudo ranges and pseudo velocities.

III. DISCUSSION

Integrated onboard guidance and navigation systems used in launch vehicles allow applying modern information technologies most appropriately to ensure the required quality (accuracy and reliability) of navigation [6, 12]. The analysis shows that the onboard integrated control systems (OICS) have a number of features, main among them being unification of respective functional groups on the level of technical solutions [15, 22]. For example, all processor sections of a computer system are the same, irrespective of the problem they solve: navigation, guidance or stabilization. This fact makes away with one of the main disadvantages of the traditional (composite) on-board control system – excess range of schematic and technical solutions [23].

Unification of schematic and technical solutions by minimizing their number and the number of hardware components results in higher system reliability, reduction in the number of control and of technological equipment, cutting of development time and, ultimately, reduction in the cost of both the system as a whole, and the process of its design [6].

As a rule, OICS are based upon computer systems connected with the external environment through data converters providing transformation of the system digital code into required physical signals with lowest corruption, or transform them back into digital codes. All logical operations onboard are performed only within a computer system. This is due to the fact that modern microprocessor exceeds several times any other element alternatively suitable for onboard systems in respect of concentration of logical possibilities. Besides, logic can be tested at the program level, which simplifies the system design process by splitting it into two almost independent stages [6]. The first stage is dedicated to creation of hardware infrastructure needed to solve a task on the board, and the second stage is meant for creation of its logical content [1].

The architecture of OICS is shaped to solve a particular set of tasks on the board and is adapted for a class of problems to be solved on the board with about 30 % redundancy. At the same time it must support communications to ensure survivability of the system, and must be able to reprogram it from outside, etc. [22].

We must note that the mentioned requirements are typical for any modern computer system and meeting them does not cause any essential difficulties. Thus, OICS have the following characteristic properties [21]:

- functional flexibility and the ability to reprogram its functions;
- high performance characteristics, i.e. a possibility of creating compact control and start-up equipment with high probability of fulfillment of the task set;
- Survivability, as in the case of failure of the equipment the system will be regenerated or switch to one of the particular algorithms, or elects self-destruction.

And finally, orientation of computer architecture to solving a particular class of specific problems provides a gain in sizes and power consumption [5]. Since, as it was already indicated above, all the logic tasks on the board are solved within the computer system, all information flows pass there through. By writing all the input information of each processor into the correspondent register it is possible (provided this element is preserved) to reproduce all states of each processor after the experiment in the laboratory conditions. This makes debugging and testing of onboard algorithms and programs less complex [24].

Start-up and control OICS equipment may access any element of the onboard computer system via a single information channel. This provides compactness of control and start-up equipment, minimum number of communications during operation of the product and high probability of fulfillment of the target task after launch (by deep pre-launch control of the onboard system via a single information channel) [1].

The process of conceptual design of the onboard integrated system for a commercial launch vehicle includes in particular synthesis of navigation and control algorithms. In its turn, the synthesis may be successfully implemented only if there are appropriate adequate models of motion of the object, permanent (predetermined) elements of control and navigation system (control actuators, gyroplatform or SINS, GPS receiver, etc.), as well as models of steering and disturbance forces and moments influencing the launch vehicle in flight.

It is obvious, that viability and efficiency of the synthesized algorithms and the adequacy of the respective models can be described in details in the present research only by imitation mathematical simulation of the process of controlled motion of the launch vehicle taking into account the whole range of steering forces and moments.

Such simulation suggests creating sets of motion and disturbance models. The first of such sets shall make a so-called model of “external environment”, and the components making the model are most explicit and exact. This refers primarily to simulation of the center of mass of LV, as well as to disturbance models. All the named models have already been described earlier [5, 10]. Here we shall only remind that in the process of creation of a “real” trajectory of LV chance factors such as divergence of initial launch conditions, error in the assembly of the stages of the launch vehicle (turn and misalignment of stages in reference to their target position), thrust deviation from the vector rated in size and directionally, variations in atmospheric density, drift and trend of output signals of gyroblocks and accelerometers, errors in tailoring of pseudo ranges and pseudo velocities owing to onboard clock bias and zenithal errors (tropospheric and ionospheric refraction), errors of actuating mechanisms will be taken into consideration as well. Non-sphericity and anomalies of Earth's gravitational field were considered as a determining disturbing influence.

Steering forces and moments shall be formed based on thrust vector of the engine and deviation of the vector owing to use of a tilting nozzle.

It should be noted that models describing operation of an integrated navigation and guidance system of a spasecraft are relatively simple because they make allowance for availability of our data about the reference trajectory, and geometrical and weight characteristics of the launch vehicle corresponding to reference values, orientation and intensity of wind, thrust, launching environment and conditions of stage separation, nominal characteristics of control and navigation system components, and statistical characteristics of errors made by navigational devices (SINS and the receiver). The model of the spacecraft gravitation fields used for solving a navigation task is much less complicated than the model used for simulation of external environment. In this research we shall suppose that the guidance task will be provision of motion of the center of mass of the launch vehicle so as to minimize its deviation from the reference trajectory. In these conditions, angular motion must be organized in such a way that the pitch channel will be oriented along the guidance plane with zero angle and zero rolling velocity. Stage separation must be done at the moment, which differs minimally from programmed in the reference motion.

We shall point out that such formulation of a guidance task is naturally simplified as much as possible, and doesn’t allow, in particular, to study the process of injecting a payload into the Earth orbit, because this process supposes manoever of the final stage, and consequently solving on board a respective boundary task in one form or another. But, as it has been many times emphasized [1, 5, 6, 10, 14, 15], the purpose of the present research is to formulate efficient and precise navigation algorithms, based on the use of SINS and the GPS - receiver. In connection with the foregoing, it is obvious that high precision solution of a navigation task will allow to implement manoevers needed to launch a payload, all other conditions being equal.

Taking the above into consideration, we may make a functional diagram of the process of simulation of operation of the onboard integrated system, as shown in Fig. 1.

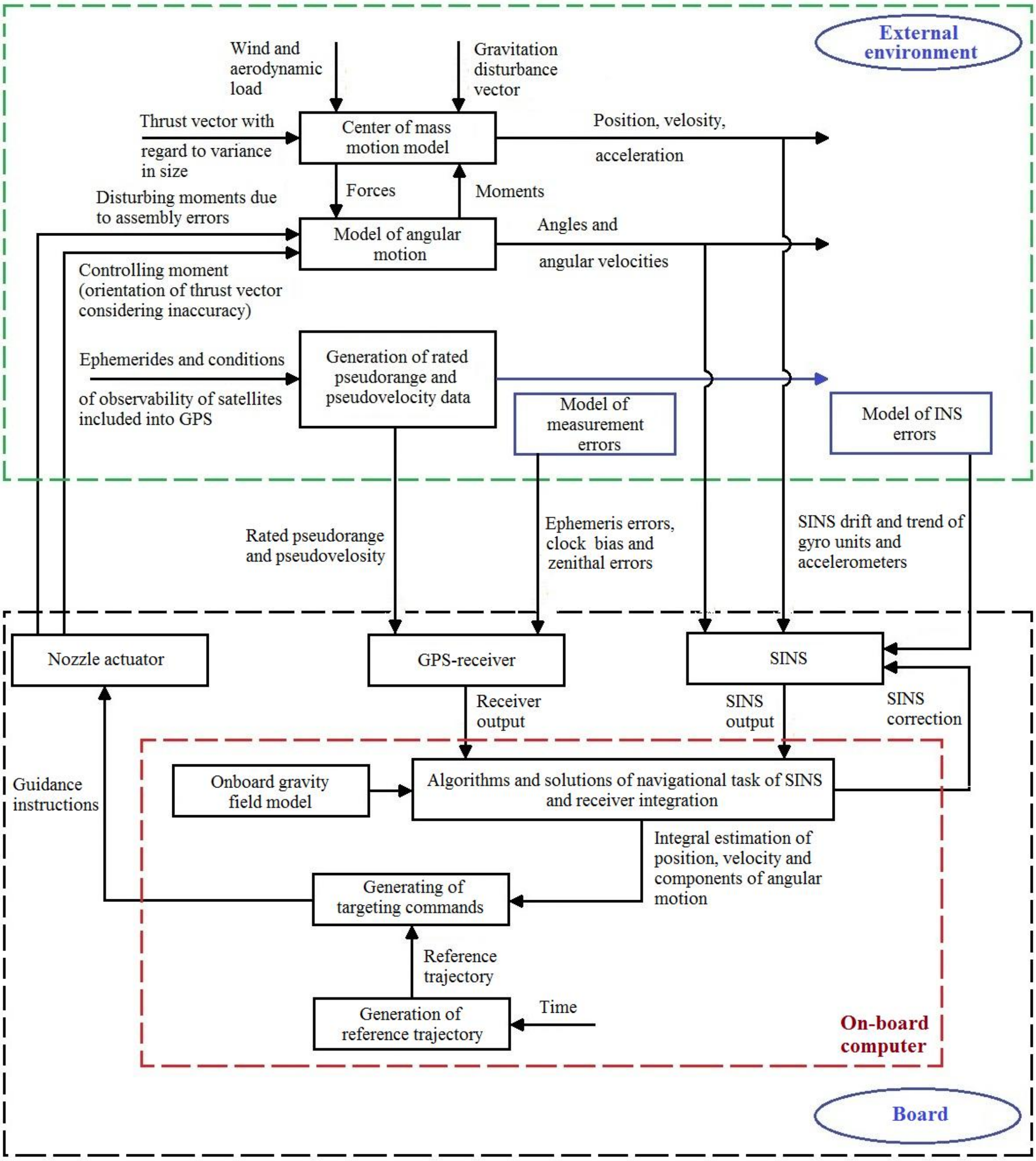

Fig. 1. Functional diagram of simulation process

3.1. Implementation of the Imitation Simulation Process

Statement of a simulation task may be illustrated using a functional scheme (Fig. 1), which suggests creation of an instrument, namely a program complex designed to implement tasks and objectives of research.

The most appropriate and suitable for the creation of such a complex is object-oriented approach (OOA). This approach makes it possible to develop a flexible and extensible Methodological Software of the required level of complexity, allowing to use hierarchical structures of inherited classes in the form of appropriate libraries, and to ensure security of stored data.

It must be noted that while using OOA, we have to determine the so-called processes and the structure of the corresponding hierarchy of these classes. This type of research is very good formalized, but, and, based on existing experience we can make the following recommendations for development of an object- oriented scheme of software and mathware:

1. All the material objects of research, such as aircraft, control systems, power meters, etc., which are the systems with a finite number of inputs and outputs must be a "black box" with a number of properties, but with a hidden mechanism of functioning.
2. It is advisable to start building up a hierarchical chain of such classes with the most general, abstract class, where only the most general fields, typical for the whole intended chain, are identified, and where methods are declared as virtual and abstract ones. In other words, in such classes only field structures and template methods are declared, and the method bodies themselves are absent. This requires overlapping them in descendant classes.
3. If complex algorithms requiring a large number of settings and additional procedures are used during the simulation, it is necessary to build up libraries for the correspondent classes that shall implement the mentioned algorithms. In such a case, the method which specifies the initial mathematical problem must be declared abstract to further overlap in the descendant within the present project (for example, the function of calculation of the right sides of the system of ordinary differential equations).
4. It is advisable that auxiliary procedures and simple algorithms should take the forms of individual modules without ascribing them to any class in order to simplify the overall structure and, as noted above, to improve the performance of the program. For example, the best thing is to collect the functions and procedures of matrix algebra, algebra of complex numbers, quaternions, tensors, etc. in separate modules, having previously described respective types (matrix, complex number, quaternion, tensor etc.).
5. If the studied processes are characterized by nesting, i.e. one process is connected directly or indirectly with several others, the class that implements this process must provide the appropriate field for the object from the class, which implements the nesting process. It should be noted that such nested objects are to be created from the outside, i.e. in the calling program with transmission of the created objects into the addressed classes. It is necessary to ensure that the different classes use only one instance of this class, and access to its data is coordinated. Thus, during the initialization of the whole structure, most independent simple objects must be created first, and thereafter complex composite objects are to be made.

Thus, considering the above, we may present the architecture of a software complex that implements the functional diagram (Fig. 1). This architecture is shown in Fig. 2 and, naturally, it repeats the architecture of the functional diagram (Fig. 1). Because when creating a software system, you should be guided by the requirements in respect of the efficient use of computing resources, as well as by the requirements regarding accuracy and speed of calculations.

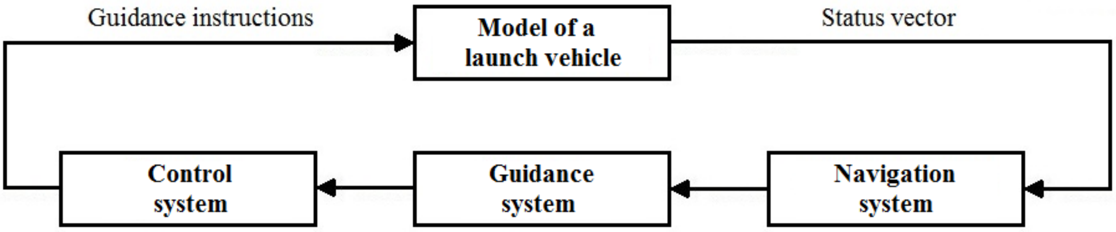

Fig. 2. Architecture of a software complex

3.2. Simulation of the LV Motion

The LV Model Block describes the dynamics of LV (as the center of mass (CM) and angular motion) influenced by forces and moments conditioned by the environment and deflection of controls. In order to determine basic classes and the corresponding chains of descendant classes implementing the element under consideration, we shall specify the required models and algorithms implementing the process of simulation of the LV dynamics with indication of the required initial data.

In its core, the problem in question is the task of integrating the system of ordinary differential equations (ODE) of the first order.

Thus, in the context of software implementation, the block contains two classes: a class that implements the numerical method of integration of ODE systems, and the class describing a model of forces and moments of uncontrolled motion of the CM and the angular motion of the LV.

Let’s consider the chain of classes implementing the library of methods of numerical integration of ODE systems (Fig. 3).

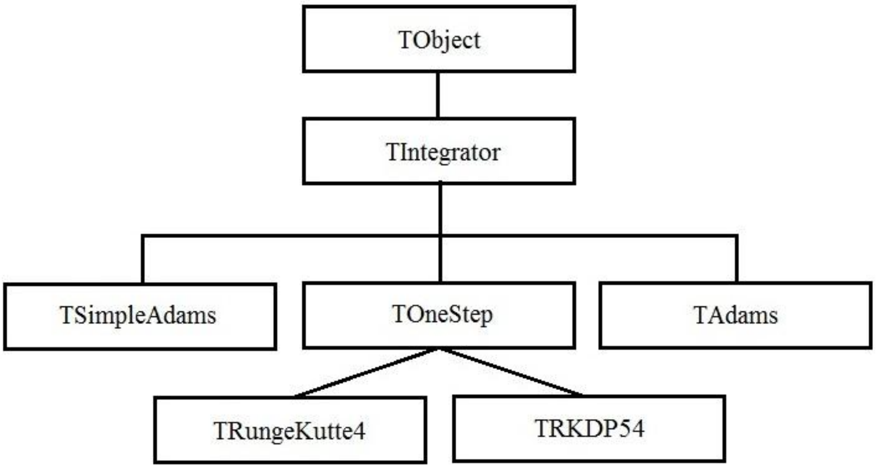

Fig. 3. Library of the methods of numerical integration of the systems of ordinary differential equations

The library contains the following methods:

- Runge-Kutte methode;
- the nested Dormand-Prince method;
- Adam-Bashforth-Moulton predictor-corrector method.

All the methods accept the nested one, have a constant integration step and lacks evaluation of local error at each step. The predictor-corrector method is an iterative one, and completion of iterations is determined either upon achievement of a given accuracy of residual error in the two last solutions, or upon achievement of a specified number of iterations.

To solve the problem of simulation of the LV dynamics we will use the nested Dormand-Prince method of the Runge-Kutte family [15], and to solve the basic navigation equation for INS, the predictor-corrector method will be used.

The full vector of the dynamic system status includes components of position, velocity of the LV in the ideal navigation coordinate system INCS, the quaternion components and output signals from drives of control motors of the LV. At the same time, we shall note that due to the discrete nature of the control loop (frequency 64 Hz), control signals are assumed to be constant during one cycle of the system controlling the operation of control engines.

The numerical integration methods themselves are described in detail in [25], and the peculiarities of the implementation of these methods regarding salvation of aerospace tasks are described in [5].

On the basis of the simulation [10, 26] we obtained dependences presented in Fig. 4-7. In Fig. 4-7 average to implementation position deviations of the LV in the ideal navigation coordinate system within the inertial navigation system [27].

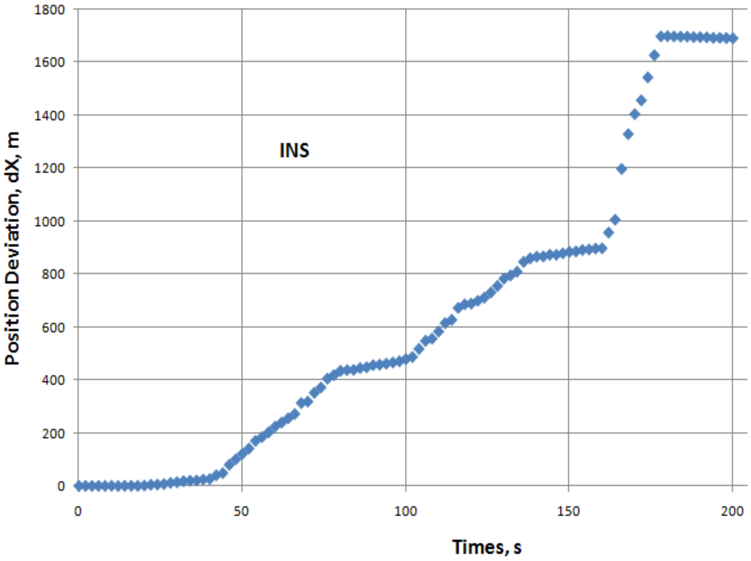

Fig. 4. Deviation of the X- coordinate

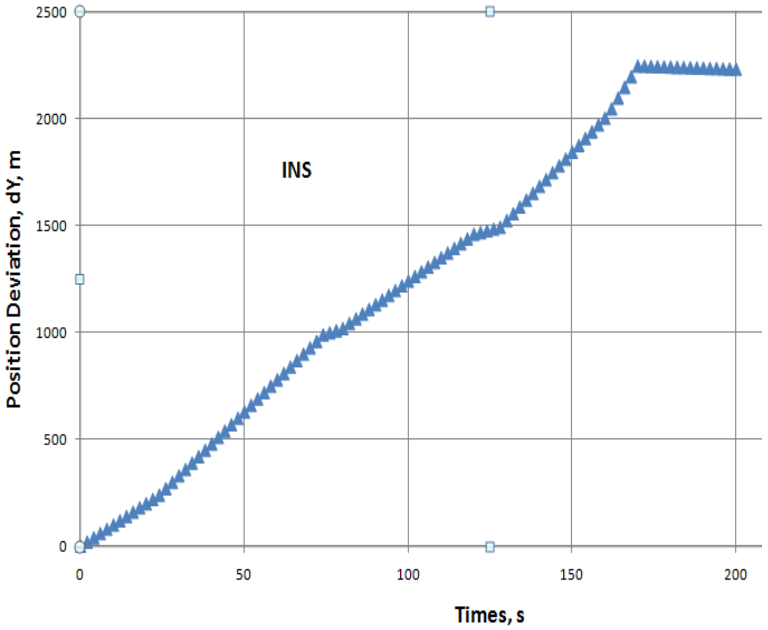

Fig. 5. Deviation of the Y- coordinate

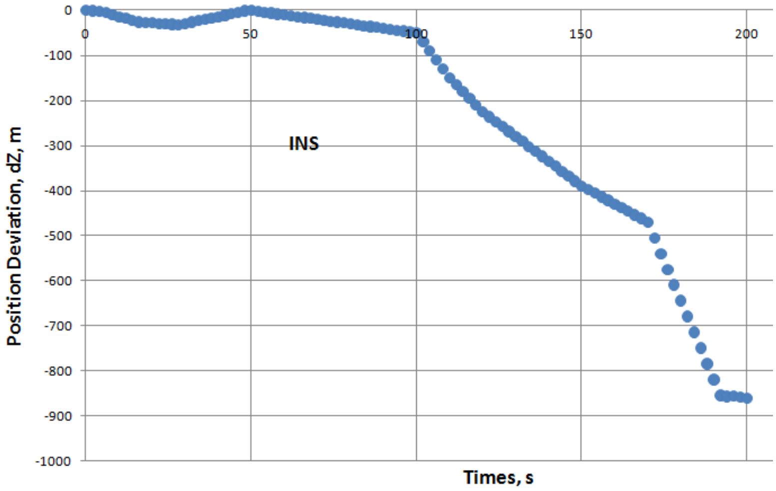

Fig. 6. Deviation of the Z- coordinate

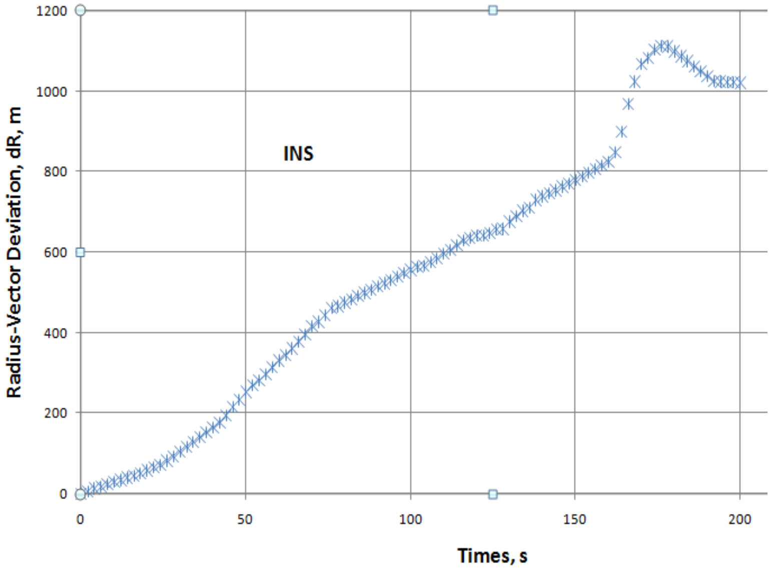

Fig. 7. Deviation of the radius-vector

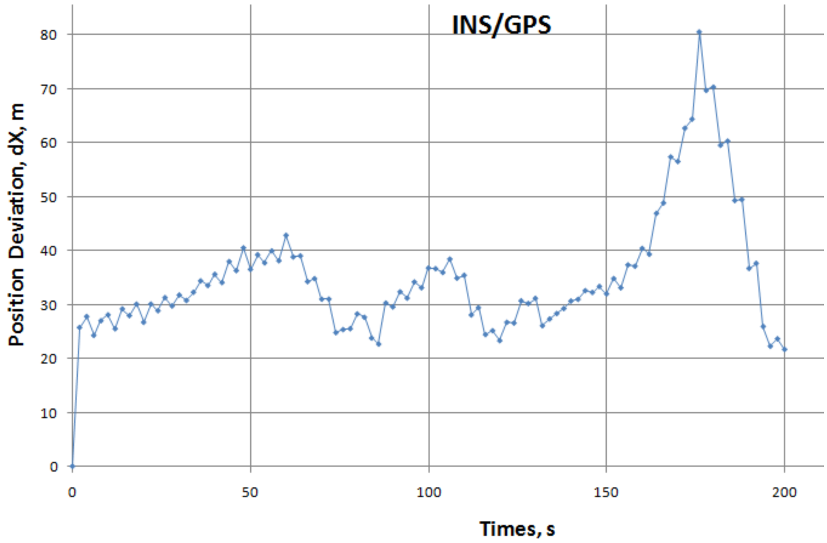

Fig. 8. Average to implementation deviation of the X-coordinate estimated by the Onboard navigation system and the GPS-receiver

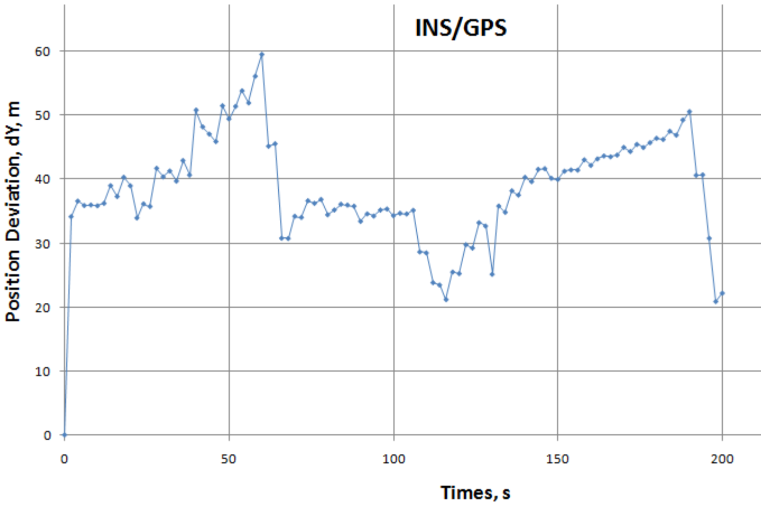

Fig. 9. Average to implementation deviation of the Y-coordinate estimated by the Onboard navigation system and the GPS-receiver

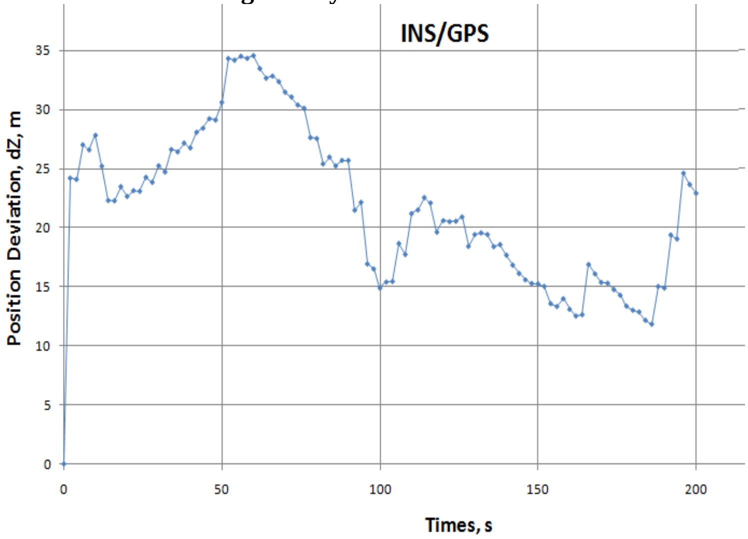

Fig. 10. Average to implementation deviation of the Z-coordinate estimated by the Onboard navigation system and the GPS-receiver

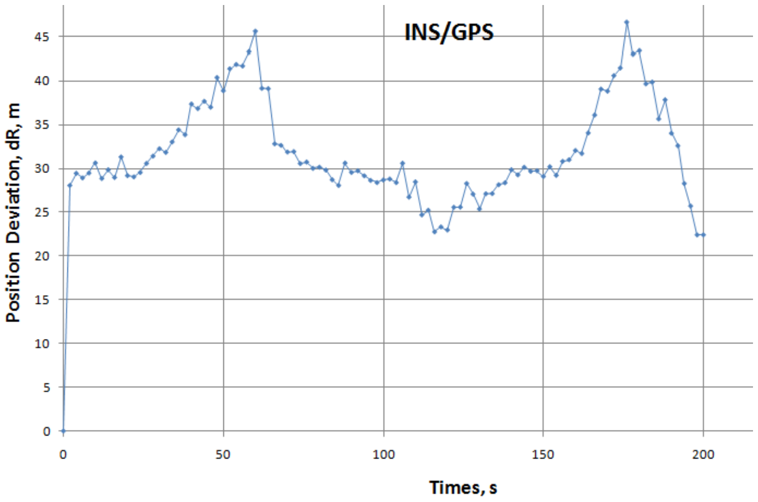

Fig. 11. Average to implementation deviation of the radius-vector estimated by the Onboard navigation system and the GPS-receiver

The Fig. 8-11 show average to implementation deviations of the position and velocity of the LV in the ideal navigation coordinate system estimated with application of the strapdown inertial navigation system (SINS) [26, 27].

The Fig. 12-15 show average to implementation deviations of position coordinates and velocity of the LV in the loosely coupled systems estimated with application of the SINS and the GPS-receiver.

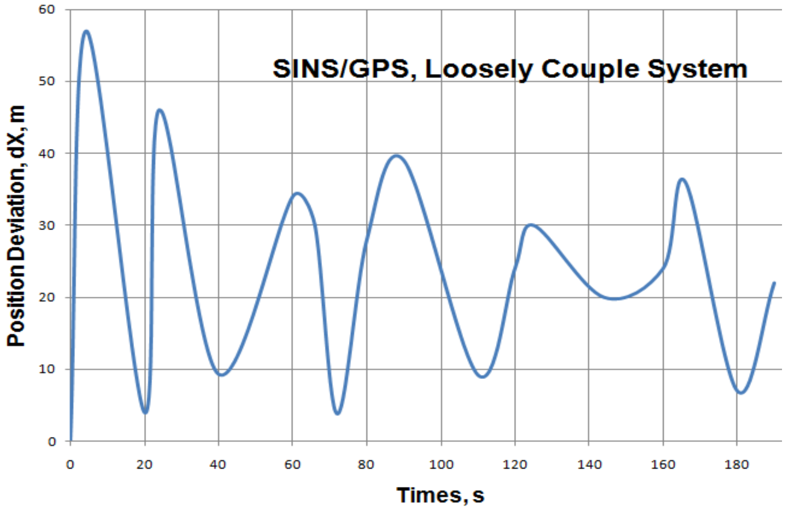

Fig. 12. Deviation of the X- coordinate

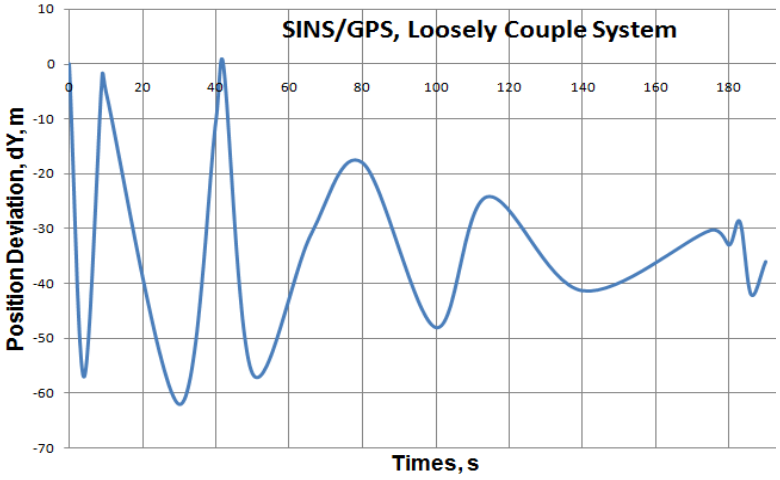

Fig. 13. Deviation of the Y- coordinate

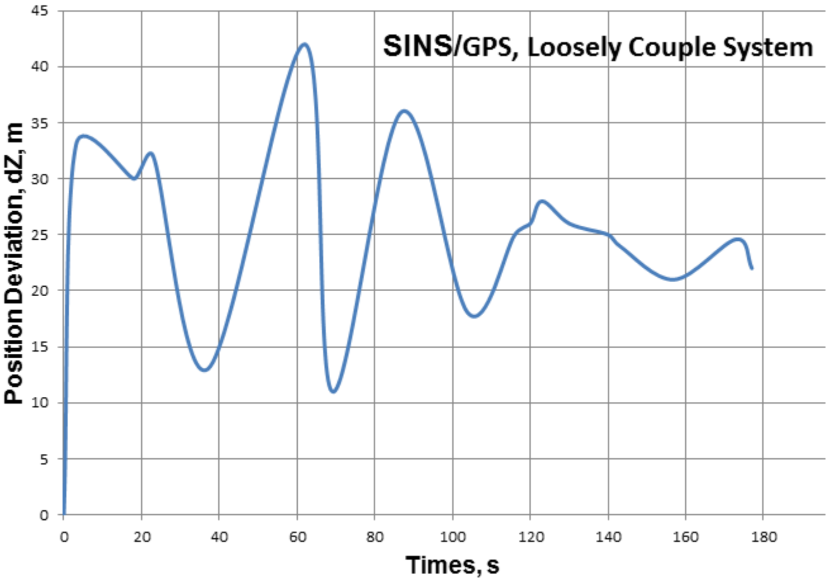

Fig. 14. Deviation of the Z- coordinate

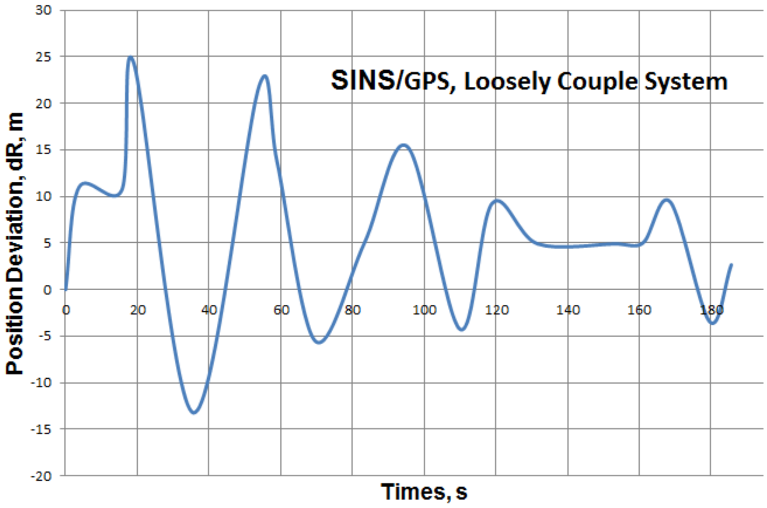

Fig. 15. Deviation of the radius-vector

IV. CONCLUSION

1. Based on the above, we have set a technical problem of the conceptual design of an integrated navigation system for the space launch vehicle qualified to inject small artificial Earth satellites into low and medium circular orbits.

2. The conceptual design of the integrated navigation system based on GPS technology involves determination of its structure, models and algorithms, providing the required accuracy and reliability in injecting payloads with due regard to restrictions on weight and dimensions of the system.

3. Offered a concept of the integrated navigation system for the commercial launch vehicle using GPS technologies.

4. Developed a system of mathematical models and algorithms providing both modeling of the process of functioning of the integrated navigation system and function simulation of the onboard navigation system of the launch vehicle itself. The system includes:

1) a model of controlled motion of the center of mass within 3 stages of the launch vehicle and relative to the center of mass, taking into account non-centrality of the gravitational field, variations in the density of the atmosphere, wind gusts, thrust distribution, assembly errors and thrust errors;

2) a model of a gyro-stabilized platform, taking into account various components of drift and accelerometer errors;

3) a model of strapdown inertial navigation system taking into account drift of gyro blocks and accelerometers' errors;

5. Positioning errors occurring during a mission of a launch vehicle using INS monotonically increase in all the coordinates and reach considerable values at the end of the powered flight phase (error along the radius vector is $\approx 3.1\,\text{km}$).
6. Based upon these simulations, we can assert that the data integration algorithm of the onboard SINS navigation information from the GPS receiver developed by us can significantly improve navigation accuracy of a launch vehicle.

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