Integrated Guidance System of a Commercial Launch Vehicle

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Abstract. This paper proposes a concept of integrated on-board 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 insert small artificial Earth satellites into low and medium circular orbits with application of GPS technologies.

1 Introduction

A key tendency in the development of affordable modern navigation systems is exposed by the use of integrated GPS/INS navigation systems consisting of a gimballed inertial navigation system (GINS) and a multichannel GPS receiver [1, 2]. The investigations show [3, 4], 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 manoeuvrable 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 next problems [1, 2, 5-7].

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 [8, 9]. 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 [9-11] is the prototype of the vehicle under development.

The planned payload delivered by the launch vehicle to a polar orbit at an altitude of ~700 km shall be 1500 kg [12]. The launch vehicle is adapting 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 71.500. Unlike most single-body launchers, this vehicle is to launch several spacecraft.

The launch vehicle under consideration is the smallest one developed by ESA [13, 14]. The injection is presenting according to the most popular and simplest (and the cheapest) scenario, more specifically: the instrument unit and the navigation system ride atop the third stage of the launch vehicle. Thus, launching until separation of the fourth stage-carrying payload is piloting in accordance

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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 centre of mass of the launcher from the preselected programmed trajectory [2, 6, 10, 12].

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 [15].

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. 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 adopting. It is required to ensure maximum accuracy in determining the vectors of position and the centre -of- mass velocity of the launcher during the flight of the 1st-3rd stages, i.e. in atmospheric and exo-atmospheric phases of the mission. This accuracy can be characterizing by the value of the dispersions posteriori of the corresponding components of the mentioned vectors [12, 16].

2 Problem Formulation

Now let us consider the possible integration schemes for GINS and GPS receiver with respect to this technical problem. As it has been aforementioned, currently we can think of three possible integration schemes as follows [2, 6, 7]:

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

The peculiarities of these schemes are discussing below. Uncoupled systems are the simplest option for simultaneous use of INS and GPS receiver [2, 6]. Both systems operate independently. However, as INS errors constantly accumulate, it is necessary eventually to make correction of INS according to data provided by the GPS receiver. 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 assess the status vector and make corrections of data provided by GINS [6].

A loosely coupled complex envisages an independent identification of navigation parameters both by GINS and by Self-Guided System (SGS). Different navigation parameters (coordinates, velocities) are provided by GINS and SGS. They are then using in the Kalman filter to determine errors occurring in GINS with a purpose of their subsequent compensation [14, 15]. The drawback is in correlation of errors, arriving from SGS to the input of the second Kalman filter and the need of strict synchronization of measurements provided by INS and SGS [6, 12].

In sources, loosely coupled systems are separating into three following types [2, 6]: the standard, "aggressive" and the so-called MAGR schemes. The difference between "aggressive" scheme and the standard one is that the former one uses the information on acceleration for extrapolation of navigation sighting executed by SGS provided by GINS in the period between measurements (Fig. 1). The Rockwell MAGR scheme uses inertial measurement from the SGS receiver made in carrier tracking loop (Fig. 2) [8].

In tightly coupled systems, the role of the INS is decreasing only to the measurement of the primary parameters of translational and rotational motions. For this reason, in such systems INS are only inertial measurement units, and the GPS receiver is without own Kalman filter. In such a structure both INS and SGS provide a series of measurements for a common computing unit [15].

Tightly coupled systems use the only "evaluator" (as a rule, the Kalman filter) that uses differences between pseudoranges and/or pseudovelocities, calculated (predicted) by INS and measured by Self-Guided System. Advantages of such a scheme described in next publications [6, 8, 12].

The disadvantages of closely coupled systems are the following [6, 8]:

- the need for special equipment for Self-Guided Systems;
- use of complex equations for measurements;
- low reliability because INS failure may result if failure of the whole system.

The later drawback can be excluding by introducing a parallel Kalman filter only for Self-Guided System [16]. Thus, the main differences between a tightly coupled system and a loosely coupled system are as follows [6, 12]:

- use of the INN output information on acceleration in the code and carrier frequency tracking loop. This allows narrowing the loop bandwidth and improving performance and tuning accuracy;
- use pseudoranges and pseudovelocities (instead of coordinates and velocities) to estimate errors in INS.

A separate embodiment of the tightly coupled systems are the so-called ultra-tightly coupled systems [12]. In such systems, estimations are undertaken in the integrated Kalman filter, and the GPS receiver is further simplified [6]. In this case, the Kalman filter is of order 40 and its implementation requires a computer with a very high speed.

Proceeding from the above information, we may conclude that an integrated navigation system of future launchers should have a structure that, depending on the functionality 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 pseudoranges and pseudovelocities.

The structure of the complex is to be open to information from other on-board navigation tools and external consumers of navigation information. This may be by introducing the corresponding input/output ports.

Clearly, the first of the above schemes using both GINS and GPS receiver is not acceptable for our task, because here the receiver is not consuming for calibration (adjustment) of GINS during the mission by evaluating the drift component. As a result, in the absence of GPS-data errors of GINS grow at the same rate as in the absence of the receiver [8].

Thus, we conclude that in the present study it is appropriate to examine both schemes of interconnection: tightly and loosely coupled, and based on the results of simulation, draw conclusions in favour of one of the possible solutions.

3 Simulation of the Operation of the Onboard Integrated System for a Commercial Launch Vehicle

3.1 Mathematical Model of Integrated Onboard System

The 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, 8]. 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 [14]. 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 [16].

The architecture of OICS is influencing to solve a particular set of tasks on the board and is adapted for a class of problems for solving 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. [7].

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 [15]:

- 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 fulfilment 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.

Finally, orientation of computer architecture to solving a particular class of specific problems provides a gain in sizes and power consumption. Since, as it was already specifying above, all the logic tasks on the board are solving 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.

3.2 Model of Inertial Navigation System

In the INS under consideration, the main components are the gyrostabilized platform and the block of integrating accelerometers. The gyrostabilized platform (GSP) embodies the on-board navigation coordinate system (ONCS). A functional circuit for INS using GSP is expressive in Fig. 1.

Figure 1. A functional circuit for INS using GSP

Functionally INS may be seeing composed of two blocks: a pre-processor and a navigational block.

3.3 Source Data for Modelling

According to mathematical models and algorithms described above, we created mathematical software for mathematical modelling of the process of nautical positions of the launch vehicle using an inertial navigation system, GPS receiver and integration algorithm for system data [7].

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 manoeuvre of the final stage, and consequently solving on board a respective boundary task in one form or another. However, as it has been many times emphasized [1, 2, 6, 12], 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 implementing manoeuvres needed to launch a payload, all other conditions being equal vectors [12, 16].

4 Simulation Results

According to mathematical models and algorithms described above, we created mathematical software for mathematical modelling of the process of nautical positions of the launch vehicle using an inertial navigation system, GPS receiver and integration algorithm for system data [6].

Figure 2. Deviation of the radius-vector dR and absolute velocity dV for Loosely Couple and Tightly Couple Systems with SINS/GPS

Based on the modelling conducted [2, 6-8, 12], we obtained dependencies, which are shown in Fig. 2.

Fig. 3 shows average in implementation values of errors in calculation of pitch and yaw angles of the launch vehicle.

Figure 3. Errors in calculations of pitch and yaw

5 Conclusion

1. Have offered a concept of the integrated navigation system of a commercial launch vehicle, based on GPS technology.
2. Have developed a complex of mathematical models and algorithms, which help model both the process of functioning of the integrated navigation system and operation of the onboard navigation system of the launch vehicle itself.
3. We have developed an object-oriented computer soft implementing all the above models and algorithms for modelling of flight of the launch vehicle with different onboard systems: a) only GSP; b) GSP+GPS receiver; c) only SINS; d) SINS+GPS receiver for: uncoupled scheme; loosely coupled scheme; tightly coupled scheme.

4. Performed mathematical simulation of the operation of the navigation system of the LV in all the above implementations confirming the efficiency of all models and algorithms.
5. It has been shown that the use of the tightly coupled system does not result in significant improvement of navigation (deviations of the radius- vector 16.2 m and of the absolute velocity m/s) attended by an increase in the cost of its elements and amplification of integration schemes.

References

1. N. Zosimovych, Commercial Launch Vehicle Design, LAP LAMBERT Acad. Publ., **184** (2016)
2. N. Zosimovych, Conceptual Design of Navigation System for a Commercial Launch Vehicle, The Int. Journ. of Eng. and Sc. (IJES), Vol. 5, **31-42**, 10 (2015)
3. Flight instruments and navigation systems: Aircraft systems (lecture notes), Politecnico di Milano, Dipartimento di Ingegneria Aerospaziale, (2004)
4. G. M. Siouris, Aerospace Avionics Systems, Acad. Press INC (1993)
5. Kyu Sung Choi, Development of the commercial launcher integrated navigation system the mathematical model, using GPS/GLONASS technique, 52nd Int. Astronautical Congr., France, Toulouse, (2001)
6. N. Zosimovych, Integrated Guidance System of a Commercial Launch Vehicle, Modern European Science – 2014, Proc. X Int. Sc. and Pract. Conf., Sheffield, **10-22**, 18 (2014)
7. N. Zosimovych, Studying Guidance System of a Launch Vehicle with Application of GPS Technologies, Бъдещето Въпроси от Света на Науката – 2015, Proc. XI Int. Sc. and Pract. Conf., Sofia, Vol. 20, **24-38** (2015)
8. N. Zosimovych, Guidance System of a Launch Vehicle with Application of GPS Technologies, Cambridge Journ. of Edu. and Sc., Vol. 3, Cambridge University Press, **647-674**, 1(15) (2016),
9. The European Small Launcher: BR-257, ESA Publ., the Netherlands (2007)
10. Vega (raketa-nositel), <http://ecoruspace.me/Bera.html>
11. Vega: User's Manual. Issue 3/Revision 0, France: Arianespace, **188** (2006)
12. N. Zosimovych, Modeling the Integrated Guidance System of a Commercial Launch Vehicle, Int. Ref. Journ. of Eng. and Sc. (IRJES), Vol. 3, **39-54**, 6 (2014)
13. R.F. Appazov, O.G. Sytin, Metody proektirovaniya traektoriy nositeley i sputnikov Zemli, M., Nauka, **440** (1987)
14. Yu.G. Siharulidze, Ballistika letatelnyh apparatov, M., Nauka, **351** (1982)
15. A.A. Lebedev, G.G. Adjimamudov, V.N. Baranov, V.T. Bobronnikov, Osnovy sinteza system letatelnyh apparatov, M., MAI, **224** (1996)
16. D.J. Bayley, Design Optimization of Space Launch Vehicles Using a genetic Algorithm, Auburn University, Alabama, **196** (2007)