Simulation modelling of autonomous navigation support for small satellite constellation

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Abstract. A small satellite system has many advantages related to its technical characteristics, production cycle and costs. At the same time, separate satellites are usually operating as a part of a ballistic-coupled constellation. The navigation and ballistic support tasks for the satellite group include calculation of satellite motion, of inter-satellite bases and prediction of the ballistic existence of the constellation. Currently, autonomous navigation support of the constellation is proved by onboard satellite navigation systems, the design cycle of which necessarily includes simulation of implemented algorithms. In the paper, the simulation model of small satellite navigation support is presented. The simulation procedure for the navigation support includes the following steps: formation the reference satellite constellation, estimation the current status of GPS and GLONASS systems orbital groupings, calculation the parameters of navigational satellite radio-visibility, solving the navigation problem according to global navigation satellite systems and inter-satellite navigation. The article also describes the procedure and results of modelling the process of the onboard navigation system functioning. Further development of the model associated with the software implementation of the small satellite disturbed orbital motion and modules for generating the radio frequency component of navigation and inter-satellite signals.

1. Introduction

The emergence of small satellite systems is the next logical step of the spacecraft industry development. The presence of standard platforms and their relative simplicity, use of general-purpose electronic components, the overall reduction in cost, timing of development, production and launch into space are key advantages of these systems [1]. At the same time, restrictions on the launch mass and dimensional characteristics, power consumption and payload cost often imply that the small satellites are usually operated as a part of a ballistic-coupled constellation in which the largest distance between the satellites is significantly less than the orbit length of the satellite group flight [2].

The ballistic-coupled constellation can be used for solving many problems, such as [3–5] research of distributed payload properties, Near-Earth objects exploration, research and design of extra-large aperture antennas, arrays and fields, implementation of multiple sequential surveys of the Earth surface or deep space objects and calibration of ground-based space observation equipment. The constellation can be considered as a distributed system: a long-baseline interferometer or a deep-space scanner in the optical or ultraviolet wavelength range. In order to maintain stable technical characteristics of this system, it is necessary to solve the following navigation and ballistic support tasks for the satellite group [6]:

- calculation and prediction of motion for each satellite center of mass;
• calculation and maintenance of the inter-satellite bases within established limits;
• prediction of the ballistic existence of the satellite cluster.

Currently, the autonomous navigation support of the constellation is proved by onboard satellite navigation systems, the principle of functioning of which can be based on Earth, Sun and navigation star optoelectronic sensors, inertial orientation systems and multichannel receivers of global navigation satellite systems (GNSS) [7–9]. Algorithmic support for autonomous navigation is an essential part of the satellite onboard control system embedded software, the development procedure of which is regulated by many international standards, such as ECSS-EST-40C and RTCA DO-178B. Analogical regulatory documents were designed by the European Space Agency to support dedicated space projects: Columbus Software Development Standard, Galileo Software Standard and others [10]. The design cycle of the control system software following modern concepts necessarily includes simulation of implemented algorithms. The simulation model can be used in the design process of the embedded software, their debugging and testing in conjunction with hardware navigation support and inter-satellite communications systems [11,12]. This paper presents the simulation model of the navigation support for the small satellite constellation and the simulation results of functioning the onboard navigation tools of the small satellite.

2. **Simulation model of the small satellite navigation support**

Consider the structural organization of the simulation model used for debugging and testing algorithms of the satellite group navigation support (Fig 1) and a functional purpose of the individual modules included in the model composition.

**Figure 1.** Block diagram of the interaction between the simulation model modules.

The simulation procedure for the navigation support is realized in the following order:

• formation the reference constellation stand on the specified orbit parameters and the relative location of the small satellite hardware simulators;
• estimation the current status of the GNSS GPS and GLONASS orbital groupings according to the operational information received from the GNSS receivers – simulators of the small satellites and data from the navigation system almanac;
• calculation the parameters of navigational satellite radio-visibility from a satellite orbit position into a low Earth or geostationary orbit;
• solving the navigation problem according to the GNSS and inter-satellite navigation, which involves the calculation of current coordinates, orbital velocity vectors and spatial orientation angles for each small satellite in the constellation;

• estimate the statistical error for measurements of the orbital coordinates and the space orientation parameters.

The module (1) is designed to calculate navigation satellites coordinates and the directional velocity vector based on the GNSS operational information in the PZ-90.11 geocentric coordinate system. In the process of modelling the following operations are implemented: decryption operational information data, correction radio navigation parameters of the navigation satellites, Lunar and Solar gravitational perturbation compensation and decision the system of differential equations of satellite space motion.

The module (2) provides the estimation of the navigation satellite coordinates and the directional velocity vector in the PZ-90.11 system according to the GNSS almanac data in the RINEX format for the specific time. The module provides the calculation of the main Keplerian and additional elements of the navigation satellite orbit such as the draconic period of Earth satellite revolution, the semi-major axis of the orbit, the eccentric and true revolution anomalies.

The module (3) is designed for assessment of the small satellite reference coordinates in the PZ-90.11 coordinate system, while the elements of the satellite orbit are specified in the NORAD TLE format. The calculating procedure for the coordinates involves the computation procedure of main and additional Keplerian elements of the orbit described in the SGP8 method [13]. The module also includes functions for calculating the relative coordinates between the elements of the small satellite constellation.

The module (4) provides the navigation data exchange with the reference GNSS receivers by using the NMEA-0183 and the specialized VIN exchange protocols via the RS-232 serial interface. The GNSS receivers are used for simulating the onboard satellite navigation system. In this case, the reference configuration of the constellation corresponds to the placement of the receiver antenna systems relative to each other, for example, on a roof or a ground test site.

The module (5) allows determining the parameters of radio-visibility zones of the navigation signals from the satellite orbit position into geostationary and low Earth orbits. The estimation is performed for grid nodes of geodetic coordinates, each of which is an under-satellite point for the standing point of the satellite into the orbit. The module also includes functions for calculating the power flux density of the navigation signal and signal-to-noise ratio according to the ITU R-REC P.619-3 recommendation.

The module (6) provides the estimation of the small satellite current coordinates and the directional velocity vector according to the GNSS GPS and GLONASS operational data. The procedure involves solving the system of nonlinear equations by the Gauss-Newton method, relating the measured value of the small satellite pseudo-range and pseudo-speed and the discrepancy of onboard time scales between the GLONASS, GPS systems and the small satellite onboard avionics.

The module (7) provides the calculation of the small satellite current coordinates and the directional velocity vector relative to the current coordinates of the satellite – constellation leader, or relative to the satellite – reference points with a known configuration of the small satellite system. The module sequentially calculates the current satellite coordinates by adding the reference values of the reciprocal coordinates between the constellation elements. The coordinates are calculated starting from the satellite located at the smallest distance from the reference point to the small satellite located on the periphery of the constellation.

The module (8) allows calculating the values of the small satellite spatial orientation angles in the PZ-90.11 coordinate system according to the GNSS operational information for the specific time. The calculation procedure involves solving the nonlinear system of equations for determining the direction cosines of the vector on the navigation satellites, taking into account a distance between antenna modules of the satellite navigation system and an angle between them. The current values of the spatial orientation angles (yaw, pitch and roll) are calculated based on the results of solving the system of
equations. The module also implements phase ambiguity compensation algorithms for received navigation signals based on the radio direction finding method.

The module (9) provides the calculation and estimation of statistical measurement errors of the current small satellite absolute and relative coordinates, the components of the velocity vector and the spatial orientation angles of the satellite.

The simulation model of the small satellite navigation support is implemented in C++ language and the Qt widget toolkit. This model is a part of the hardware-software complex for the satellite reciprocal navigation modelling (Fig 2).

**Figure 2.** Block diagram of the hardware-software complex for the satellite navigation modelling.

In addition to the software tools, the complex includes:

- two reference MRK-101 GNSS receivers (manufactured by JSC «NPP «Radiosviaz», Russia) for simulation the onboard navigation systems, the antenna systems of the receivers are placed on motorized suspension devices;
- Keysight N9342C handheld spectrum analyzer;
- the hardware-software simulator of the GNSS measurement information.

The simulator of the GNSS measurement information is based on the PXI standard modular measuring platform (National Instruments, USA) which includes the PXIe-1085 chassis, the PXIe-8880 embedded controller and a set of additional modules. The measurement information simulator includes the following modules: wide-bandwidth vector signal generator PXIe-5673E, 6-drive data storage module HDD-8261 and serial interface module PXI-8430.

Based on the simulator of measurement information signals, navigation signals are generated and fed to the instrumentation antennas or the onboard navigation system simulators directly. The simulators receive and initially process the navigation signals directly from the GNSS satellites and the simulator of GNSS measurement information. Secondary signal processing is performed by the modules that compose the simulation model of the satellite navigation support. The embedded controller provides functional control of the GNSS simulator. The portable spectrum analyzer is used for controlling the spectrum of the navigation signal.

3. **Functional modelling of the on-board satellite navigation system**

Briefly consider a procedure and results of modelling the process of the onboard satellite navigation system functioning. As a prototype for simulated small satellites was chosen the PRISMA satellite constellation, implemented by the collaboration of Swedish Space Corporation, German Aerospace Centre and French National Centre for Space Studies in 2010 [14]. The PRISMA small satellites were
developed to demonstrate methods and tools of autonomous inter-satellite navigation: a vision-based sensor and an inter-satellite link [15]. Table 1 presents the structure and the orbital parameters of the ballistic-coupled PRISMA constellation.

| 1. Reference system, orbital regime | Geocentric, Sun-synchronous |
| 2. Semi-major axis, km | 7 086.0 |
| 3. Perigee altitude, km | 668.3 |
| 4. Apogee altitude, km | 749.0 |
| 5. Orbital inclination, deg | 98.267, 98.536 |
| 6. Longitude of the ascending node, deg | 310.776, 270.322 |
| 7. Orbital eccentricity | 0.056, 0.042 |
| 8. Argument of periapsis, deg | 66.400, 222.394 |
| 9. Mean anomaly, deg | 294.315, 137.400 |
| 10. Mean motion, revolution per day. | 14.560, 14.424 |
| 11. Anomalous period, min. | 98.900, 99.833 |

During the simulation period in one day, the constellation made about one hundred full revolutions around Earth. In this case, the solution of the navigation problem, calculation of absolute to Earth and relative coordinates of the small satellite position in space was carried out in the continuous mode with the statistical root-mean-square error presented in Table 2.

| 1. Error for the current absolute coordinates, m | x-axis – 1.68, y-axis – 1.84, z-axis – 1.93 |
| 2. Error for the velocity vector components, m/s | x-axis – 0.02, y-axis – 0.02, z-axis – 0.01 |
| 3. Error for the spatial orientation angles, arcmin | yaw – 6.08, pitch – 6.29, roll – 5.48 |

| 1. Error for the current absolute coordinates, m | x-axis – 4.42, y-axis – 7.80, z-axis – 5.47 |
| 2. Error for the velocity vector components, m/s | x-axis – 0.02, y-axis – 0.02, z-axis – 0.02 |

According to the test results, it was found that the simulation model of the small satellite navigation support corresponds the established requirements, in particular, according to the statistical error for the current relative coordinates – no more than 0.02 m; the relative velocity – no more than 0.01 m/s and the spatial orientation angles – no more than 20 arcmin by using the antenna system with the distance between the individual antenna modules of 0.7 m.

4. Conclusion
The development of software for autonomous navigation of the small satellite constellation involves the extensive use of simulation tools for implemented algorithms. The simulation model of the small satellite navigation support using GNSS GPS and GLONASS is proposed. The proposed model provides formation with the reference configuration of the satellite constellation, calculation the current
state of GNSS groups and their radio-visibility zones, solution of the navigation problem according to the GNSS and inter-satellite navigation with a statistical assessment of the results.

Further development of the model may be associated with the software implementation:

- models of the satellite orbital motion, taking into account the effect of air resistance, light pressure, the Sun and Moon attraction;
- modules for generating the radio frequency component of the navigation signal and the signal of the inter-satellite radio link.

It is also planned to use this model for the automated generation of the satellite control system software, which can be deployed both on specialized processors supporting the MIL-STD-1750 or ECSS-E-ST-50-12C architecture, as well as on general-purpose system-on-chip solutions.

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