Method of Determining the Angular Orientation of Small Satellites in Orbit

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Annotation

This article provides an analysis of modern technical solutions for determining the angular orientation of small satellites in orbit. Problematic issues in improving the accuracy of the orientation and stabilization are considered. Using an additional radio navigation landmark, a new method has been devised to increase angular orientation determination reliability of the repeater satellites of the "distributed satellite" network that utilizes a Kalman filter. At the same time, it became possible to determine the orientation of the repeater satellites of the "distributed satellite" network with the usage of a measured signal value of an additional radio navigational landmark, the signal of which can be steadily received on board the root satellite.

Keywords

Small spacecraft, angular orientation, Kalman filter, distributed satellite, satellite network, radio navigation landmark, repeater satellites.

1. Introduction

Currently, small spacecraft (SC) weighing less than 100 kg are in demand [1–3]. The reasons for the rapid development of this type of satellite are the relatively low cost and the insignificant time required for designing and manufacturing of small spacecraft (SSC), and the low cost of its launch. The array of tasks carried out with the help of small spacecraft is exceptionally wide. For example, microsatellites are used to capture images of the Earth in detail at a resolution of 6–10 m [4–6]. Such satellites could be used to resolve fire detection problems, examine natural disaster zones, and carry out environmental monitoring. Their use for remote sensing, monitoring, and space research is especially relevant [7, 8].

In addition, there are reasons for the increasing popularity of the SSC. SSCs provide miniaturization of onboard systems and the new circuit solutions related to multi-satellite groups. The use of SSCs has significantly reduced the mass of the devices and solved the problems that were traditionally carried out by "large" devices, particularly in the field of remote sensing and communications. SSCs are relatively inexpensive, easily modified to accommodate a particular task, create less radio interference, and provide a significant effectiveness increase of obtaining consumer surveillance data by creating a required number of small device groups. Their use helps to reduce the risks associated with orbital launch and space work by decreasing financial losses in the event of such a satellite's failure or loss.

SSCs allow us to develop new technologies and effectively solve some specific problems of space research in various fields of science (astronomy, astrophysics, space physics, planetary science, space biology). Smaller mass SSCs (nano-, etc.) are used to establish space activities, allowing to implementation of space programs of universities. With the help of SSCs as pilot projects, small

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business organizations, and non-space companies, in general, have an opportunity to enter the space market. Overall, the development of the SSC technology could be considered as one of the fundamental drivers of the creation and development of a new generation of commercial space projects and companies.

Along with accuracy requirements for spacecraft orientation and stabilization, there are highly technical and operational requirements:

- Low weight, size, energy consumption, and cost
- High reliability (operational life of SSC must be at least 5 years).
- Low complexity.
- Minimum time required for ground testing and launching preparation.

It is clear that, on the one hand, the small size and weight of SSCs and standardization of their design contribute to a steep reduction in cost and ease of the development of new SSC models, but on the other hand it limits the level of their functionality compared to traditional spacecraft. Recently, targeted efforts have been made to expand SSC capabilities. However, despite the dynamic process of improving the characteristics of the pico and nano spacecraft, these devices cannot yet provide serious competition for well-developed traditional spacecraft.

Ensuring accuracy requirements of orientation and stabilization of small spacecraft remains a problematic issue. The orientation accuracy of most of the currently launched single SSCs “CubeSat” is limited and is about 10 [9, 10]. Their orientation is usually determined using inertial magnetic and solar sensors. Magnetic actuators are most often used for control. Digital triaxial magnetometers are usually used to determine the orientation. Solar panels could be used as solar sensors, where current varies depending on the orientation to the Sun or photodiodes located on the facets of the satellite.

Today, a promising technology that aims to improve the functional characteristics and reliability of CubeSat is a technology of autonomous operation of the spacecraft [11, 12]. Such technologies include the organization of spacecraft flight in low Earth orbit in a “formation” or “swarm” [13, 14]. Spacecraft formation is a type of mission in which several aircraft fly in a short distance (up to several hundred meters) from each other. In contrast to the traditional orbital grouping of satellites, where the devices act independently while performing a common task, in spacecraft formation those devices act together, distributing individual functions and elements of the task between individual devices. In essence, we are talking about the creation of distributed satellite systems. In this case, the limitation on the composition of the payload is significantly reduced. For example, the transmission of target and/or telemetry information to Earth can be carried out through a special satellite equipped with a telemetry system with high bandwidth for the transmission of data collected by other devices. In distributed systems, in contrast to the “swarm,” SSC can be spaced over long distances [15, 16].

Therefore, from this point of view, there is a need for domestic researches that is aimed at the development of a low-orbit satellite communications system, which is a group of low-orbit spacecraft (LEO-system) with a “distributed satellite” architecture [17–20].

Fig. 1 reflects 1, 2 are root satellites; 3–8 are satellite repeaters of micro-group A; 9, 10 are distributed satellites of micro-group A; 11, 12 are feeder lines of micro-group A; 13 - a service area of the satellite communication system; 14, 15 are feeder lines of micro-group B; 16, 17 are distributed satellites of the micro-group B; 18–23 are satellite repeaters of micro-group B; 24 is inter-satellite terahertz line between distributed satellites.

The direction of research for the creation of low-orbit satellite systems with a “distributed satellite” architecture is new, so to ensure their further practical use, special attention should be paid to the synthesis of algorithms and methods in order to increase the structural and functional reliability of determining the angular orientation of the repeater satellites of the “distributed satellite” network.

The aim of this article is to develop a method for determining the angular orientation of small satellites in orbit. This will increase the structural and functional reliability of determining the angular orientation of repeater satellites of the “distributed satellite” network that utilizes a Kalman filter.

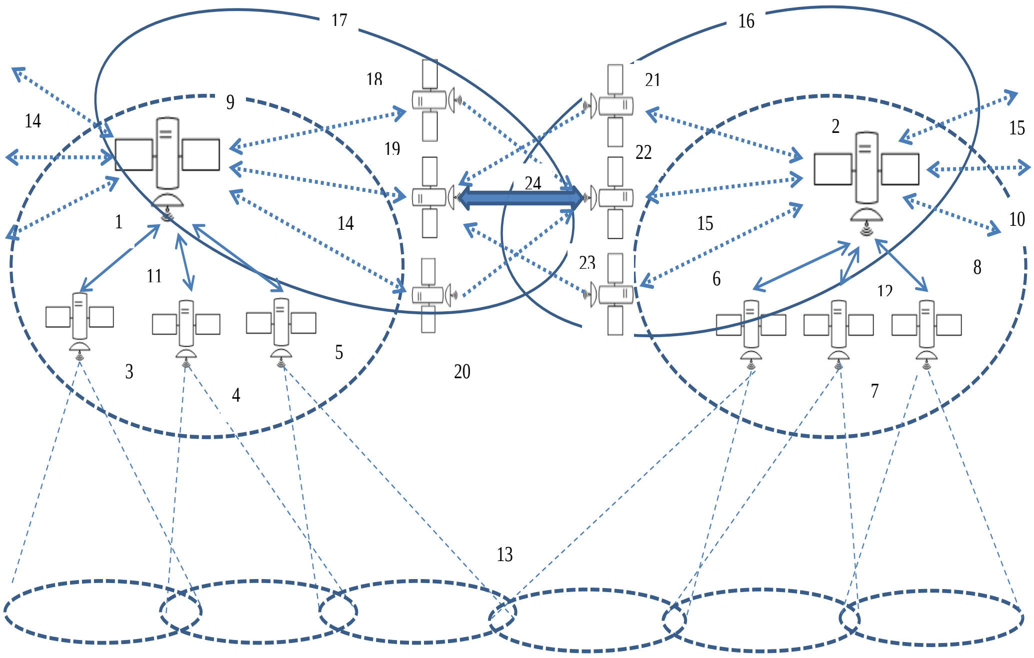

Figure 1: Low-orbit satellite communication system with terahertz communication channels

2. Statement of the Main Material

2.1. Consideration of Modern Technical Solutions for Determining the Angular Orientation of Small Satellites in Orbit

There is a method for determining the angular orientation of the object by using the navigational radio signals of the navigation spacecraft (NSC) of global navigation satellite systems (GNSS). This method is based on the reception of signals from one or more NSCs by two or more antenna receivers that are parallel to one or two axes of the object, signal selection with Doppler frequency, determining the phase difference for the time interval measurement and determining the angular orientation of the object. During the time interval measurement, several estimations of the phase difference between the pairs of antennas are performed, and the angular orientation of the object is determined by solving a system of equations [21]. The disadvantage of this method is the inability to determine the orientation of the moving object.

There is also a correction method when the movement is out of the atmosphere. The essence of this method consists in measuring the linear parameters of at least one GNSS NSC moving along a known orbital trajectory, forming correction parameters vector accordingly to the obtained data, repeating these operations at successive time intervals, and correcting the inertial navigation system (INS) using the generated correction parameters [22].

The disadvantage of this method is the need to create a feigned acceleration due to the inclusion of the propulsion system of the spacecraft, which, firstly, leads to the consumption of energy resources and reduction of the lifetime of the spacecraft. Secondly, it limits the use of the spacecraft for its intended purpose during the activation period of the propulsion system, as well as the periods of preparatory and final operations that are necessary to create the apparent acceleration.

There is a method of correcting the INS of the spacecraft, based on measuring the angular relative parameters of two stars using optical sighting telescopes [23].

The drawbacks of the NSI correction method of measuring the relative two-star angle parameters are:

1. The possibility of illumination of optical devices.
2. The need to carry out preliminary operations for the scheduling of measurement sessions, including the complex processing of the star catalog, in order to determine the reference stars for

measuring direction vectors for which there are favorable conditions for orbital flight, excluding the illumination of optical telescopes.

3. Relatively high costs of optical telescopes.

4. The need for long measurement sessions of the directional vectors on the stars to ensure the necessary accuracy in determining the orientation parameters, during which the use of the spacecraft for the intended purposes is limited.

There is a well-known domestic technical solution [24] in which the low-orbit satellite communication system is a group of low-orbit spacecraft (LEO-system) with a "distributed satellite" architecture, including a group of the root (leading) satellites and repeater satellites. Around each root satellite, a micro-group of repeater satellites called a "distributed satellite" is formed. The functions of the root satellite at the selected phase point of the orbital plane of the working orbit are performed by mini or micro-satellites, and the functions of the repeater satellites are performed by CubeSat's. The root satellites are interconnected in a ring network by high-speed communication lines between the satellites.

The geometric size of a "distributed satellite" is the area around a root satellite with a radius of about 1 km. This means that the CubeSat's carry out a group flight at a distance less than 1 km from the root satellite. The space segment of the LEO system consists of different orbital planes with the same number of distributed satellites, the same method, and differing in the length of the ascending node. In each orbital plane, the distributed satellites are evenly spaced with the same relative true anomaly, with each distributed satellite connected to the two adjacent distributed satellites in its orbital plane and the two nearest distributed satellites in the two adjacent orbital planes - one in each orbital plane.

The disadvantage of this solution is that:

1. It does not show the architecture of the positioning system.

2. It is not possible to assess the technical characteristics and technical capabilities of the low-orbit satellite radio system for the provision of quality services in integrated 5G and IoT networks.

The following article [25] presents a method for measuring the distance between spacecraft in a low-orbit "distributed satellite" system, which makes it possible to analytically determine the relative position of spacecraft and measure the speed of relative motion of the final and root satellites. The obtained data are the source of calculation of the orbital motion of each spacecraft.

2.2. The Essence of the Proposed Method for Determining the Angular Orientation of Small Satellites in Orbit

The objective of the proposed innovative solution is to improve the system of low-orbit satellite communications. The expected result of this solution is to increase the structural and functional reliability of determining the angular orientation of the repeater satellites of the "distributed satellite" network that utilizes a Kalman filter.

The problem is solved by adding to the system of low-orbit satellite communication system a GPS antenna, a GPS receiver, an inertial sensor set, an inertial device unit, an additional Kalman filter, and an additional unit for determining the orientation parameters of the micro-group of repeater satellites (additional radio navigation landmark).

The technical result obtained by this method shows the increased reliability in determining the angular orientation of the repeater satellites of the "distributed satellite" that utilizes a Kalman filter due to the additional radio navigation landmark and the ability to determine the orientation of the satellite repeaters according to the measured value of the signal of the additional radio navigation landmark, the signal of which can be steadily received on board of the root satellite. In addition, the application of the proposed method allows controlling the parameters of the orientation of the INS for most of the time of the orbital flight by determining the systematic error of inertial orientation and then, if necessary, adjust the parameters of the spatial inertial orientation of the INS by making corrections.

The essence of the proposed method can be explained as follows: suppose that the onboard equipment of the group of the root (leading) satellites (SC) and repeater satellites (slave) of the satellite network of the "distributed satellite" includes INS. In this way, it is assumed that as appropriate signal sources to determine the orientation of the SC, NSC GNSS or terrestrial stationary radio stations could be used, the signal of which can be reliably received by the onboard equipment of the SC. The spatial orientation of the coordinate axes of the connected coordinate system of the root (leading) satellites is carried out according to the data from INS and at some flight interval t, the angular position control system orients the connected coordinate axes of the root (leading) satellites parallel to the axes of the orbital coordinate system.

The position orientation system in the orbit of the repeater satellites of the low-orbit satellite micro-grouping system "distributed satellite" operates as follows: a scanning radio photon radar is installed on the root satellite, and the miniature optical sensors are installed on the repeater satellites, which are located on the sides of the satellites by groups. On each side panel, the location of such a group should be unique, thus the exact side and precise repeater satellite location in space will be determined. Knowing the size of the observed satellites and the exact location of the miniature optical sensors on each facet, it is possible to determine the coordinates of the vertices of the CubeSat in relation to the root satellite.

2.2.1. The Algorithm for Determining the Orientation Parameters of the Micro-Grouping of Repeater Satellites Relative to the Root Satellite

Suppose that the coordinates axes for which the state of the satellites is considered are arranged as follows: the *OY* axis is directed vertically upwards, the *OX* axis is in the direction of the satellite's motion, and the *OZ* axis is on the right for an observer looking along the *OX* axis. The position of the slave satellite-repeater relative to the master (root) is determined by three Euler angles. Let's determine the matrices of the guide cosines in the transition from the original coordinate system *OXYZ* to the coordinate system $OX_b\, Y_b\, Z_b$, associated with the body of the master satellite. First, consider the rotation of the satellite from its original position relative to the *OX* axis at an angle ψ counterclockwise, if it is observed from the positive part of the *OY* axis:

$$A_\psi = \begin{bmatrix} \cos\psi & 0 & -\sin\psi \\ 0 & 1 & 0 \\ \sin\psi & 0 & \cos\psi \end{bmatrix} \quad (1)$$

The matrix A_ψ is an operator that converts the initial coordinates *X*, *Y*, *Z* into the coordinates *X'*, *Y'*, *Z'*.

Similarly, consider the rotation at an angle ϑ relative to the axis *OY'* counterclockwise when observed from the positive side of the intermediate axis *OZ'*:

$$A_\vartheta = \begin{bmatrix} \cos\vartheta & \sin\vartheta & 0 \\ -\sin\vartheta & \cos\vartheta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Similarly, we obtain a table by rotating the angle γ counterclockwise relative to the intermediate axis *OZ''* when observed from the positive part of the intermediate axis *OX''* [27]:

$$A_\gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{bmatrix} \quad (3)$$

The full chain of transformations is as follows:

$$[X_b\, Y_b\, Z_b] = A_\gamma [X'\, Y'\, Z'] = A_\gamma A_\vartheta\, [X''\, Y''\, Z''] = A_\gamma A_\vartheta A_\psi\, [X\, Y\, Z] \quad (4)$$

Let's introduce the notation:

$$A = A_\gamma\, A_\vartheta\, A_\psi \quad (5)$$

where the matrix *A* is the desired transformation matrix from the initial coordinate system *OXYZ* to the coordinate system $OX_b\, Y_b\, Z_b$ associated with the root satellite. The result is the following:

$$[X_b\, Y_b\, Z_b] = A\, [XYZ] \quad (6)$$

In this case, matrix *A* will have a certain structure. And since the matrix of guide cosines *A* is orthogonal, the inverse matrix *B* can also be determined:

$$B = A \wedge T \quad (7)$$

Matrix B allows to go back from the coordinate system that is associated with the root satellite to the original coordinate system:

$$[XYZ] = B\,[X_b\;Y_b\;Z_b] \tag{8}$$

Thus, it is possible to determine the orientation parameters of the micro-grouping of repeater satellites relative to the root satellite.

The following iterative algorithm is proposed to measure the distance from the root satellite to the micro group of repeater satellites.

2.2.2. The Interpolation Algorithm for Measuring the Distance to the Micro-Grouping of Satellite Repeaters using Radio Photon Radar

In order to solve this problem, we will need to use a method of measuring the range of the target in the near radar, in which the oscillations received in the radar station are sampled in an analog-to-digital converter. Then the envelope of the received signal with a large signal-to-noise ratio is allocated. Next, the time delay of the received signal up to the sampling period is determined, which shows the distance to the target [28].

The disadvantage of this solution is that the errors of phase measurement will be insignificant only at high signal-to-noise ratios. In addition, the sampling rate must be selected for specific signal parameters, as the errors of the signal phase measurement depend on the sampling rate. Therefore, it is necessary to determine the sampling frequency intervals at which the phase difference is measured most accurately. The authors do not provide a method for selecting the sampling frequency, so the practical application of this method is difficult.

Let's consider an improved algorithm proposed by the authors to estimate the temporal position of the radio signal to measure the distance to the micro-grouping of repeater satellites.

Suppose that at some interval of analysis there is an addictive mixture of useful signal and noise:

$$x(t) = s(t, \tau_0, A_o, \mu_0) + n(t), \tag{9}$$

where $n(t)$ is white Gaussian noise with spectral density $N_{0,}$

$$s(t, \tau, A, \mu) = A\varphi(t-\tau)\cos(\omega_0\, t - \mu), \tag{10}$$

where *s(t, τ, A, μ)* is a useful signal of duration T; A, μ is a priori unknown amplitude and phase of the signal, approximately constant in the interval of signal duration; ω_0 is carrier circular frequency; $\varphi\,(t)$ is an a priori unknown function, which is determined in the general case by the digital sequence used, as well as the band-limiting signal filter; τ is the unknown time position of the signal from the a priori interval $[0, \tau_{max}]$.

Next, we apply the method of maximum plausibility of the signal time position estimation [29]. The parameter τ in (9) is estimated, and the unknown parameters of the signal A, μ - are accompanying. In the presence of accompanying parameters, it is necessary to maximize the functionality of the likelihood ratio for these parameters. The decision is made in favor of the value of the time position at which the maximized likelihood ratio takes the greatest value [29].

The logarithm of the maximized likelihood ratio functional in estimating the time position will look like the following:

$$Q(\tau) = \frac{2}{N_0 T}\left(Y_1^2(\tau) + Y_2^2\,(\tau)\right), \tag{11}$$

$$Y_1\,(\tau) = \int_{\tau}^{T+\tau} x(t)\varphi(t-\tau)\cos(\omega_0\, t)dt$$

$$Y_2\,(\tau) = \int_{\tau}^{T+\tau} x(t)\varphi(t-\tau)\sin\omega_0\, t)dt$$

Estimation of the maximum plausibility of the parameter τ is based on the position of the maximum of the output signal (11)

$$\tau_m = \arg\sup Q(\tau) \quad (12)$$
$$\tau \in [0, \tau_{max}].$$

Usually, the receiver produces (11) not for all, but only for N discrete values $\tau_n, n = 1, N$ from the a priori interval $[0, \tau_{max}]$ shifted relative to each other by some value ε. The decision on the value of the time position τ is made by the channel number with the largest output signal (11), so the value τ_m is used for an estimation where:

$$Q(\tau_m) \geq Q(\tau_n), n \neq m, n = 1, N. \quad (13)$$

The statistical evaluation of the parameter τ, in this case, depends not only on the energy parameters of the useful signal and noise but also on the value of the discrete Δ. It can be shown that the following approximate expression is valid for the time position estimation dispersion from which it follows that the accuracy of the estimation, in this case, is significantly limited by the discrete Δ. In this regard, the authors propose to improve the accuracy of the temporal position estimation of the signal by using several values of the decisive function (11).

In the proposed interpolation algorithm in accordance with (13) the time position τ_m with the maximum value of the decisive function $Q(\tau_m)$ is selected. In addition, the values of the crucial function of adjacent time positions $Q(\tau_{m-1})$, $Q(\tau_{m+1})$ are taken. We use quadratic interpolation to estimate the time position.

Fig. 2 shows the curves of the normalized unconditional dispersion of time position estimation of the interpolation algorithm on the signal-to-noise ratio z. The results of calculations are obtained by computer simulations for different values of the number of discrete output signals of the receiver for chip duration V.

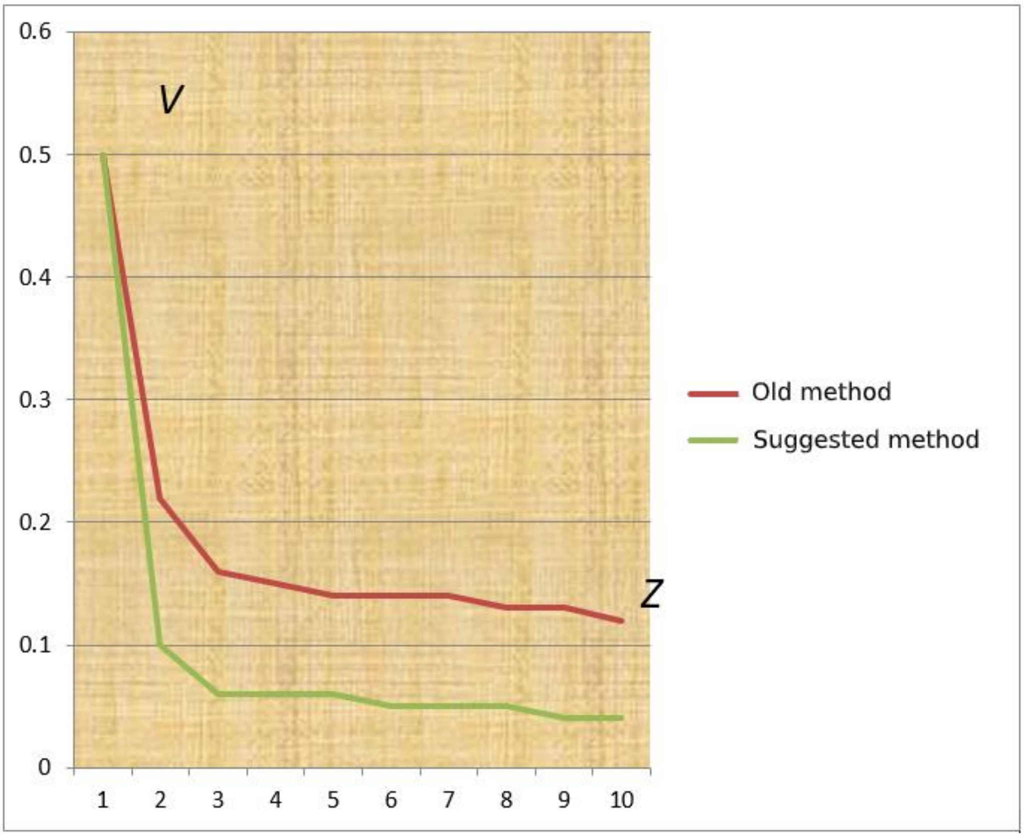

Figure 2: The dependencies of the time position estimation normalized unconditional dispersion of the interpolation algorithm on the signal-to-noise ratio z for different values of the number of discrete output signals of the receiver on the chip duration V.

From Fig. 2 it is seen that the characteristics of the proposed algorithm are significantly exceeding the characteristics of the algorithm (13) in the region of a small signal-to-noise ratio. In addition, the unconditional dispersion of the proposed algorithm decreases with an increased signal-to-noise ratio.

Thus, based on the new structure of the integrated architecture consisting of GNSS-receiver, INS system, additional radio navigational landmark, and integration means, the reliability of determining the angular orientation of repeater satellites of the "distributed satellite" network that utilizes a Kalman filter has been increased.

2.3. Technical Device for the Practical Implementation of the Proposed Method

The proposed method can be implemented by a device, the block diagram of such a device is shown in Fig. 3.

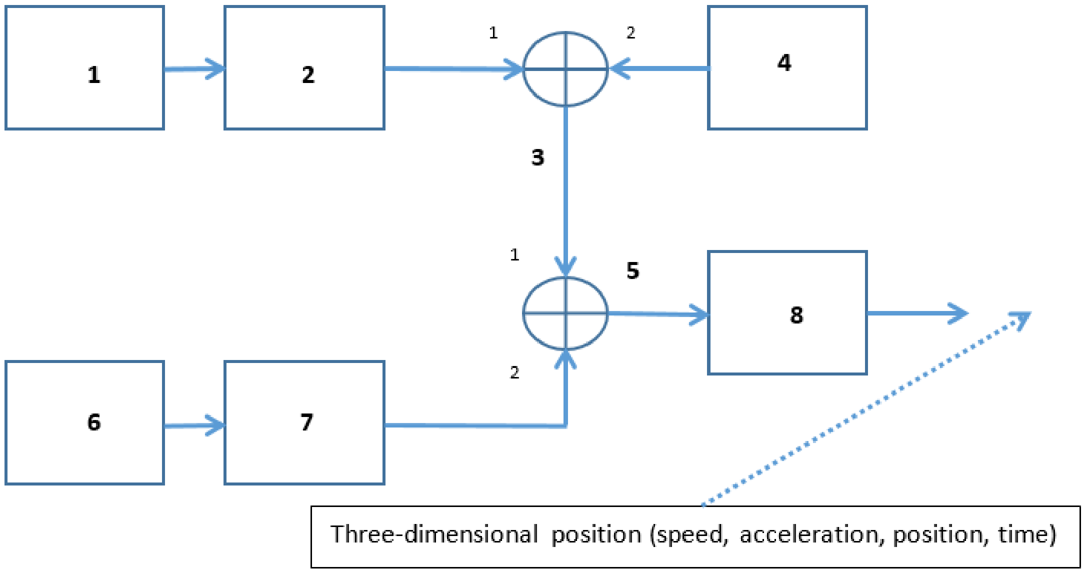

Figure 3: Block diagram of the device for the proposed method implementation

Fig. 3 shows 1 is GPS antenna, 2 is GPS receiver, 3 is set of inertial sensors, 4 is inertial device unit, 5 is additional Kalman filter, 6 is an additional unit for determining the orientation parameters of the micro-grouping of satellite repeaters (additional radio navigation landmark), 7 is an infrared device.

The device works as follows: system measurements at the input of KAF 8 are the position of the satellite and its speed calculated by a set of inertial sensors 4, GPS - receiver 2, and an additional unit 6 are used for determining the parameters of orientation. Their difference is taken in such a way as to determine the vector of observations of the complementary KAF 8.

If GNSS is disabled due to environmental conditions, the GNSS solution may be available for an extended period of time regardless of the state of the GPS receiver 2.

The equation of observations for such an architecture can be written as:

$$z_k^l = H^l x_k + v_k^l \tag{14}$$

where $z_k^l = \pi_k^1 - \pi_k^2 - \pi_k^3$ is an observation vector; $\pi_k^1 = [p_k^1 \; v_k^1 \,]^T$ is a vector of body position and velocity, which is estimated by the GPS receiver at time *k;* $\pi_k^2 = [p_k^2 \; v_k^2 \,]^T$ is a vector of body position and velocity, which is estimated in INS at time *k;* $\pi_k^3 = [p_k^3 \; v_k^3 \,]^T$ is a vector of body position and velocity, which is estimated by an additional radio navigation landmark at time *k;* H^l is the observation matrix for the proposed architecture will have the following form:

$$H^l = \begin{bmatrix} I_3 & 0_3 \; 0_3 \; 0_3 \\ 0_3 & I_3 \; 0_3 \; 0_3 \end{bmatrix} \tag{15}$$

It should be noted that in the proposed method, the system of which is presented in (14), is linear. Thus, assuming that it is Gaussian, the problem can be solved using the Kalman filter [30].

The use of small satellites reduces the cost of the mission and its preparations, but it is associated with difficulties due to severe constraints on energy and computing resources on board. These limitations also apply to the orientation management system. Active control of the microsatellite orientation requires the device's motion determination relative to the center of mass in real-time. Recursive algorithms for estimating motion parameters such as the Kalman filter [30] allow us to obtain the best estimation of the state vector of the device relative to the center of mass based on orientation measurements of the sensors and microsatellite motion model. However, the limitations of computing resources onboard the microsatellite do not allow to take into account many inaccuracies in the model of motion that act both from the external environment and caused by the imperfect orientation of the control systems. In addition, the measurements of the orientation sensors due to unaccounted factors may differ slightly from the measurement model used by the detection algorithm. Therefore, there is a need for further investigation of the influence on the accuracy of motion detection due to inaccuracies and factors that are not considered in the motion model.

3. Conclusions

A new method has been devised, its technical result shows the increase of the angular orientation determination reliability of repeater satellites of the satellite network "distributed satellite" that utilizes a Kalman filter. The effect is achieved by using additional radio navigational landmarks and the ability to determine the orientation of repeater satellites according to the measured value of the signal of the additional radio navigation landmark, the signal of which can be steadily received on board the root satellite.

In order to optimize the use of energy capabilities of repeater satellites of the "distributed satellite" network and increase the efficiency of tasks according to the mission, it is proposed to transfer the channel for measuring orbital motion parameters and flight control of repeater satellites to the root satellite network, which is a new method and has never been used in world practice.

Measuring the distance according to the interpolation algorithm between spacecraft in the "distributed satellite" allows us to determine the relative position of spacecraft and measure the speed of relative motion of the final and root satellites. The obtained data are the source for calculating the parameters of the orbital motion of each spacecraft.

Thus, using the proposed method it is possible to achieve, above all, the following advantages: along with the high accuracy of the three-dimensional positioning solution, it is possible to simultaneously achieve high availability, continuity, and integrity of the solution of the positioning problem within a limited spatial area. The possibility of achieving a high speed of updating solutions for positioning problems is provided.

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