

UDC 517.977.5-629.783

Doi: 10.31772/2712-8970-2021-22-4-649-659

**Для цитирования:** Оптимальное управление разведением спицы трансформируемого рефлектора при наличии возмущений / С. А. Кабанов, Д. С. Кабанов, Е. Н. Никулин, Ф. В. Митин // Сибирский аэрокосмический журнал. 2021. Т. 22, № 4. С. 649–659. Doi: 10.31772/2712-8970-2021-22-4-649-659.

**For citation:** Kabanov S. A., Kabanov D. S., Nikulin E. N., Mitin F. V. Optimal control of deployment of the spoke of a transformable reflector in the presence of disturbance. *Siberian Aerospace Journal*. 2021, Vol. 22, No. 4, P. 649–659. Doi: 10.31772/2712-8970-2021-22-4-649-659.

## Оптимальное управление разведением спицы трансформируемого рефлектора при наличии возмущений\*

С. А. Кабанов, Д. С. Кабанов, Е. Н. Никулин, Ф. В. Митин<sup>1</sup>

Балтийский государственный технический университет «ВОЕНМЕХ» имени Д. Ф. Устинова»  
Российская Федерация, 199005, г. Санкт-Петербург, 1-я Красноармейская ул., 1

<sup>1</sup>E-mail: fedor28@list.ru

*Одним из перспективных видов космических аппаратов являются крупногабаритные трансформируемые рефлекторы. Такие аппараты доставляются на заданную орбиту в сложенном виде, а затем разворачиваются до рабочего состояния. Большая апертура позволяет значительно расширить возможности антенны. При этом возникают задачи плавного и надёжного раскрытия, настройки формы радиоотражающего сетеполотна, регулировка орбитального положения. Ввиду того что процесс раскрытия занимает длительное время, учёт возмущающих воздействий является важной проблемой. Наличие радиации, большого перепада температур, солнечного ветра оказывает влияние на всю систему и, главным образом, на диаграмму направленности. Также необходимо плавно раскрыть элементы конструкции, так как с увеличением диаметра радиоотражающей поверхности возрастают моменты инерции антенны, что приводит к длительным колебаниям. В данной работе рассмотрен процесс разведения спицы рефлектора при наличии возмущений и ошибок измерений. Решение задачи представлено с использованием теоремы разделения.*

*Для оценивания параметров системы при наличии шумов измерений применен фильтр Калмана. Показана его работоспособность при различных значениях интенсивности шума. В качестве внешних возмущений и шумов измерений выбран случайный процесс типа белого шума. Задача управления решается при использовании алгоритма оптимального управления по иерархии целевых критериев. Показана возможность минимизации энергетических затрат путем интервального включения измерительных датчиков. Представлены результаты численного моделирования.*

\* Исследование выполнено при финансовой поддержке РФФИ в рамках научного проекта № 20-08-00646а.  
The reported study was funded by RFBR according to the research project No 20-08-00646a.

*Ключевые слова: алгоритм последовательной оптимизации, крупногабаритный трансформируемый рефлектор, оптимальная фильтрация, математическая модель, моделирование.*

## Optimal control of deployment of the spoke of a transformable reflector in the presence of disturbances

S. A. Kabanov, D. S. Kabanov, E. N. Nikulin, F. V. Mitin<sup>1</sup>

Baltic State Technical University "VOENMEH" named after D. F. Ustinov  
1, 1 Krasnoarmeyskaya St., St. Petersburg, 199005, Russian Federation

<sup>1</sup>E-mail: fedor28@list.ru

*One of the promising types of spacecrafts are large-size transformable reflectors. Such apparatuses are delivered to a target orbit folded, and then deployed to a working condition. The large aperture allows significantly expanding the capabilities of the antenna. In this case, the tasks arise of a smooth and reliable deployment, adjusting the shape of a radio-reflecting net, and adjusting the orbital position. Due to the fact that the deployment process takes a long time, accounting for disturbing influences is an important problem. The presence of radiation, large temperature differences, solar wind affect the entire system and mainly on the directional diagram. It is also necessary to smoothly deploy the structural elements, since with an increase in the diameter of the radio-reflecting surface, the moments of inertia of the antenna increase, which leads to prolonged oscillations. In this paper, the process of deployment of the reflector spokes in the presence of disturbances and measurement errors is considered. The solution to the problem is presented using the separation theorem. To estimate the parameters of the system in the presence of measurement noise, the Kalman filter is applied. Its performance is shown at various values of the noise intensity. A random process such as white noise was selected as external disturbances and measurement noises. The control problem is solved using the optimal control algorithm according to the hierarchy of target criteria. The possibility of minimizing energy costs by means of interval switching on of measuring sensors is shown. The results of numerical simulation are presented.*

*Keywords: sequential optimization algorithm, large-size transformable reflector, optimal filtration, mathematical model, modeling.*

### Introduction

Space antennas play an indispensable role in aerospace communications, military reconnaissance, deep space sensing, global broadcasting, Earth remote sensing, and climate forecasting. Because of the limitations imposed by a launch vehicle, deployable antennas are widely used [1–3]. They are placed in the fairing during the launch phase, after reaching the orbit the deployment process begins, and finally the parabolic reflecting surfaces are formed. Stable and reliable deployment of the reflector largely ensures the success of the space mission.

Since the late 1960s, large-sized transformable antennas have been actively used because of their large aperture and low mass. At present, the Astro Mesh Reflector is the most perfect and reliable deployable antenna available [4; 5]. The deployment process is completed by fixing the truss and forming the desired shape of the reflective surface.

For the vast majority of such designs, deployment is irreversible and there are no effective ways to maintain and actively adjust the radio-reflective net in orbit. It is important to study and simulate the deployment process at the design stage to get a deep understanding of the deployment dynamics [6]. The complex kinematic and dynamic behavior of the system, high nonlinear stresses and different cable network topologies, as well as energy dissipation caused by friction, damping, and gaps significantly affect the deployment dynamics of large-sized transformable antennas. Research in dynamic modeling for the deployment of different types of structures is actively being conducted [7; 8].

Here we consider the realization of a large-sized space construction using a cable system to create the necessary shape of the radio-reflecting surface of the reflector (Fig. 1) [9–12]. A large-size trans-

formable reflector (LTR) consists of a spacecraft (SC) 1. It has deployable elements attached to it, such as solar panels 2, irradiating system 3. To provide a given directional pattern, the boom 4 extends the reflector 5 to the required focal distance. The reflective surface is the netweave 6.

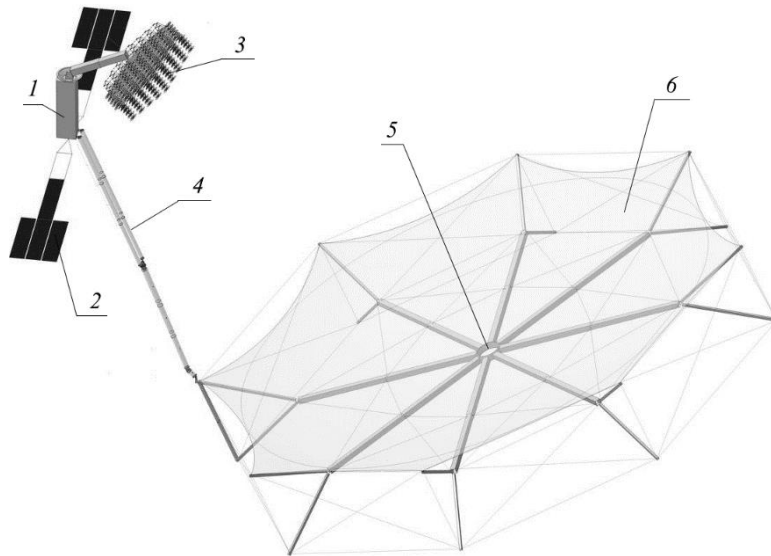


Рис. 1. Конструкция КТР

Fig. 1. The design of the LTR (Large-sized transformable reflector)

The important problem at opening of the LTR from the folded position into the set position with high accuracy of an output to stops is the account of perturbing influences. Also it is necessary to smoothly open elements of the structure, as with increase in diameter of a radio-reflecting surface the moments of inertia of the antenna increase, that leads to long damping oscillations. The presence of radiation, large temperature differences, and solar wind affect the entire system, and mainly the directional diagram [13; 14]. Therefore, it is necessary to solve the problems of filtering and control of the reflector opening.

### Mathematical description of the problem

Consider the process of direct opening of a LTR spoke. It is necessary to change the position of the spoke by a given angle  $\varphi$  under the action of force  $M$  (Fig. 2). The spoke is rigidly fixed with one end to the SC, the rotation is carried out under the action of an electric motor.

The mathematical model describing this process has the form  $\mathbf{X} = \mathbf{f}(\mathbf{X}, u, t) + \xi_x$ , where  $\mathbf{X} = (\varphi \ \omega \ a_1 \ V_{1a})^T$  is state vector;  $\xi_x = [\xi_{x1} \ \xi_{x2} \ \xi_{x3} \ \xi_{x4}]^T$  are disturbances with intensity  $\mathbf{B}_x = \text{diag}(B_{x1}, B_{x2}, B_{x3}, B_{x4})$ ;  $u$  is control vector;  $t$  is time;  $\varphi$  is spoke rotation angle;  $\omega$  is spoke rotation angular velocity;  $a_1$  and  $V_{1a}$  are time-dependent bending and spoke bending velocity, respectively. In the element-by-element form, the system is represented as follows [15]:

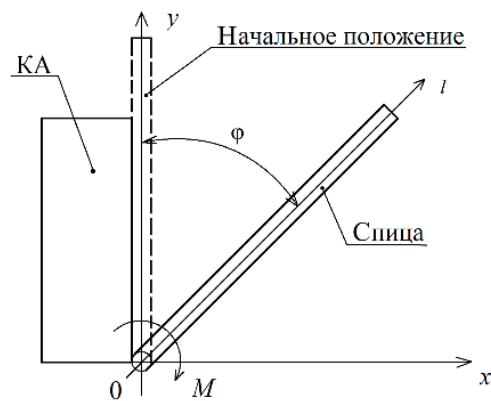


Рис. 2. Разведение спицы рефлектора

Fig. 2. Spreading of the reflector spoke

$$\begin{aligned}
 \dot{\varphi} &= \omega + \xi_{x1}, \\
 \dot{\omega} &= \frac{M(U, \varphi, \omega)}{I} + \xi_{x2}, \\
 \dot{a}_1(t) &= V_{1a}(t) + \xi_{x3}, \\
 \dot{V}_{1a}(t) &= -\frac{EI_{\text{bend}}}{\rho S} q_1^4 [a_1(t) + \gamma V_{1a}(t)] + \frac{2}{\rho S b_1(L)} \frac{M(U, \varphi, \omega)}{R_d} + \xi_{x4},
 \end{aligned} \tag{1}$$

where  $I$  is the moment of inertia of the spoke;  $E$  is the modulus of elasticity;  $I_{\text{bend}}$  is the bending moment of inertia;  $\rho$  is the material density of a spoke;  $S$  is the area of a spoke in a cross-section;  $l$  is the spoke length coordinate;  $\gamma$  is the damping coefficient;  $M$  is total moment acting on the spoke:  $M(U, \varphi, \omega) = M_p(U) - M_{\text{fr}} - M_{\text{stop}}(\varphi, \omega) - M_f(\varphi, \omega)$ ;  $M_p$  is the net torque produced by the commutatorless machine;  $U$  is the supply voltage of the commutatorless machine;  $M_{\text{fr}}$  is the friction torque;  $M_{\text{stop}}$  is the moment created by a stop;  $M_f$  is the moment created by a fixer;  $h(t, l) = a_1(t)b_1(l)$  is spoke bending [10; 11; 15; 16];  $a_1(t)$  are functions of time  $t$  only;  $b_1(l)$  are functions of coordinate  $l$  only;  $q_1 = Z/L$ , where  $Z_1 = 1,875$ ,  $L$  is the total length of the spoke;  $R_d$  is the radius of the motor shaft.

The control is performed by changing the supply voltage of the commutatorless machine  $U$ ,  $|U| \leq U_{\text{max}}$  ( $U_{\text{max}} = 12.5$  V). The net torque depends on the control  $U$  [10]  $M_p = m_{\text{ph}} p E_0 U \sin \vartheta / (\omega_p X_s)$ , where  $m_{\text{ph}}$  is the number of rotor phases;  $p$  is the number of pole pairs of magnetic field;  $E_0$  is the effective value of electromotive force (EMF) on stator winding;  $\vartheta$  is the mismatch angle (between  $U$  and  $E_0$ , for motor it is within  $[0, \pi/2]$ );  $\omega_p$  is the angular speed of motor rotor;  $X_s$  is the synchronous resistance.

We consider the spoke as a cylindrical tube. Let's take it as a single-link construction. The angle of rotation of the spoke and the bend at its end are available for measurement. For the problem of spoke separation, we consider the equations of observation in the form of

$$\mathbf{z} = \mathbf{h}(x, t) + \xi_z, \tag{2}$$

where  $\mathbf{z} = [z_1 \ z_2]^T$ ,  $\mathbf{h}(x, t) = [\varphi \ d(L)]^T$ , ( $d(L) = a(t)b(L)$ ),  $\xi_z = [\xi_{z1} \ \xi_{z2}]^T$  are random processes of white noise type with intensity  $\mathbf{B}_z = \text{diag}(B_{z1}, B_{z2})$ .

In accordance with the separation principle, the control problem is preceded by the problem of estimating the state vector by incomplete data given by equation (2) [17–19]. The optimal estimation can be obtained with a Kalman filter, the equations of which for this problem will be of the form

$$\begin{aligned}
 \frac{d\hat{\varphi}}{dt} &= \hat{\omega} + R_{11} B_{z1}^{-1} (z_1 - \hat{\varphi}) + R_{13} b_1(L) B_{z2}^{-1} (z_2 - \hat{d}), \\
 \frac{d\hat{\omega}}{dt} &= \frac{M}{I} + R_{21} B_{z1}^{-1} (z_1 - \hat{\varphi}) + R_{23} b_1(L) B_{z2}^{-1} (z_2 - \hat{d}), \\
 \frac{d\hat{a}_1}{dt} &= \hat{V}_{1a} + R_{31} B_{z1}^{-1} (z_1 - \hat{\varphi}) + R_{33} b_1(L) B_{z2}^{-1} (z_2 - \hat{d}),
 \end{aligned} \tag{3}$$

$$\begin{aligned}
 \frac{d\hat{V}_{1a}}{dt} &= -\frac{EI_{u32}}{\rho S} q_1^4 (\hat{a}_1 + \gamma \hat{V}_{1a}) + \frac{2}{\rho S b_1(L)} \frac{M}{R_d} + \\
 &+ R_{41} B_{z1}^{-1} (z_1 - \hat{\varphi}) + R_{43} b_1(L) B_{z2}^{-1} (z_2 - \hat{d}),
 \end{aligned}$$

$$\dot{\mathbf{R}} = \mathbf{f}_x \mathbf{R} + \mathbf{R} \mathbf{f}_x^T - \mathbf{R} \mathbf{h}_x^T \mathbf{B}_z^{-1} \mathbf{h}_x \mathbf{R} + \mathbf{B}_x,$$

$$\mathbf{R}(t_0) = \mathbf{R}_0. \tag{4}$$

Here

$$\mathbf{f}_x = \partial \mathbf{f} / \partial x, \quad \mathbf{h}_x = \partial \mathbf{h} / \partial x, \quad \mathbf{h}_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & b_1(L) & 0 \end{bmatrix},$$

$$\mathbf{f}_x = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{EI_{\text{bend}}}{\rho S} q_1^4 & -\frac{EI_{\text{bend}}}{\rho S} q_1^4 \gamma \end{bmatrix}, \quad R_{ii}(t_0) = 9\sigma_{xi}^2, \quad i = \overline{1, n},$$

the remaining elements of the initial covariance matrix of the estimation errors were assumed to be equal to zero.

The spoke is driven by an actuator, which is represented by a Phytron phySPACE series commutatorless electric motor [20]. The accuracy is 3–5% for 1.8°. A RangeVision Standard Plus laser scanner with an accuracy of  $\pm 0.03$  mm is used to measure the spoke deflection  $h$  [21]. A LIR-MA208 encoder [22] with an accuracy of  $\pm 1^\circ$  is used as an angular position sensor.

Требуется перевести спицу из начального положения  $\mathbf{X}(0) = (0 \ 0 \ 0 \ 0)^T$  в конечное  $\mathbf{X}(t_f) = (\pi/2 \ 0 \ 0 \ 0)^T$  с отсутствием перерегулирования по углу разворота  $\varphi$  за время  $t_f = 90$  с при наличии внешних возмущений  $\xi_x$  и шумов измерений  $\xi_z$ .

It is required to move the spoke from the initial position  $\mathbf{X}(0) = (0 \ 0 \ 0 \ 0)^T$  to the final  $\mathbf{X}(t_f) = (\pi/2 \ 0 \ 0 \ 0)^T$  with no overshoot in the rotation angle  $\varphi$  for a time  $t_f = 90$  s in the presence of external perturbations  $\xi_x$  and measurement noise  $\xi_z$ .

### Statement of the control problem

We consider a hierarchy of target functionals of the form

$$J_1 = \mathbf{V}_{f1}(\mathbf{X}, t_f), \quad (5)$$

$$J_2 = \mathbf{V}_{f2}(\mathbf{X}, t_f) + \int_{t_0}^{t_f} [f_0(\mathbf{X}, t) + 0,5(u^2 + u_0^2)^2 k^{-2}] dt, \quad (6)$$

where  $V_{f1} = 0,5\beta_1[\omega(t_f) - \omega_f]^2$ ;  $V_{f2} = 0,5\Delta\mathbf{X}_f^T \mathbf{p}_k \Delta\mathbf{X}_f$ ;  $f_0 = 0,5\beta_2[\varphi(t) - \varphi_f]^2 + 0,5\beta_3 h^2$ ;  $\mathbf{a} = \text{diag}(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ ;  $\beta_1, \beta_2, \beta_3, k$  are given coefficients;  $\Delta\mathbf{X}_f = \mathbf{X}(t_f) - \mathbf{X}_f$ ,  $\mathbf{X}_f = (\varphi_f \ \omega_f \ a_{1f} \ V_{1af})^T$  are the given final values of the corresponding variables in (1). Since  $h(t, L) = a_1(t)b_1(L)$ ,  $V_{1a}(t, L) = V_{1a}(t)b_1(L)$ , then  $a_1(t) = h(t, L)/b_1(L)$  and  $a_1(t_f) = h(t_f, L)/b_1(L)$ .

The solution of the control problem of spokes dilution according to a hierarchy of criteria in deterministic formulation is presented in detail in [16]. The control problem was also solved by control algorithms by the maximum principle using numerical methods of Newton and Krylov – Chernousko, an algorithm based on the PID control structure, and an algorithm of control structure parameter correction [10; 11; 15]. The application of the sequential optimization algorithm according to the hierarchy of target criteria makes it possible to solve the problem in real time with the absence of long damping oscillations after the spoke reaches a given angle of turn. With the help of this algorithm, it is possible to achieve the required accuracy and quality of system control.

### Modeling

We take the time of opening of a spoke  $t_f = 90$  s, the maximum permissible amplitude of deflection  $h_{\text{max}} = 10$  mm. Value of attenuation coefficient  $\gamma = 0.04$  s. Number of rotor phases  $m_{\text{ph}} = 2$ , number of pole pairs of magnetic field  $p = 2$ , effective value of EMF in stator winding  $E_0 = 2,5$  V, synchronous resistance  $X_s = 22 \cdot 10^{-3}$  Ohm, mismatch angle between rotor and stator field  $\vartheta = \pi/10$  at any load,  $\omega_p = 247$  rad/s.

The following parameters of the spoke were taken at modeling [10]: material ABS plastic QHF - 0140: material density  $\rho = 1600$  kg/m<sup>3</sup>, modulus of elasticity (Young)  $E = 1,2 \cdot 10^{11}$  Pa, spoke length  $a$

= 9,75 m, spoke mass (all the nested links)  $m = 32$  kg. We consider a spoke with ring-shaped cross-section with outer radius  $R = 0.26$  m and inner radius  $r = 0,25$  m. The moment of inertia  $I$  will be equal to  $I = mR^2/2 + ma^2/3 = 1015,4$  kg · m<sup>2</sup>. Bending moment of inertia  $I_{\text{bend}} = \pi R^3 \delta = 5,52 \cdot 10^{-4}$  m<sup>4</sup>, where  $\delta$  is the thickness of the pipe (spoke) wall.

We assume that the perturbations do not exceed  $\pm 1$  % of the maximum values of the corresponding variables. In the calculations, noises  $\xi_x$  and  $\xi_z$  were assumed to be white with intensities  $\mathbf{B}_x = \text{diag}(0,02, 0, 0.0001, 0)$ ,  $\mathbf{B}_z = \text{diag}(0,02, 0,0005)$  respectively. The initial values of the estimation errors were given as:  $\hat{\varphi}(t_0) = \varphi(t_0) + \Delta\varphi(t_0)$ ,  $\hat{\omega}(t_0) = \omega(t_0) + \Delta\omega(t_0)$ ,  $\hat{a}_1(t_0) = a_1(t_0) + \Delta a_1(t_0)$ ,  $\hat{V}_{1a}(t_0) = V_{1a}(t_0) + \Delta V_{1a}(t_0)$ , where  $\Delta\varphi(t_0) = 0.1$  rad,  $\Delta\omega(t_0) = 0.002$  rad/s,  $\Delta a_1(t_0) = 5 \cdot 10^{-5}$  m,  $\Delta V_{1a}(t_0) = 0.01$  m/s.

Fig. 3 shows the simulation results: graphs of dependences  $\varphi(t)$  (over the entire optimization interval) and  $h(t)$  (over the first 10 s). One can see that it was possible to solve the problem, i.e. to open the spoke from the initial position by a given angle  $\pi/2$ .

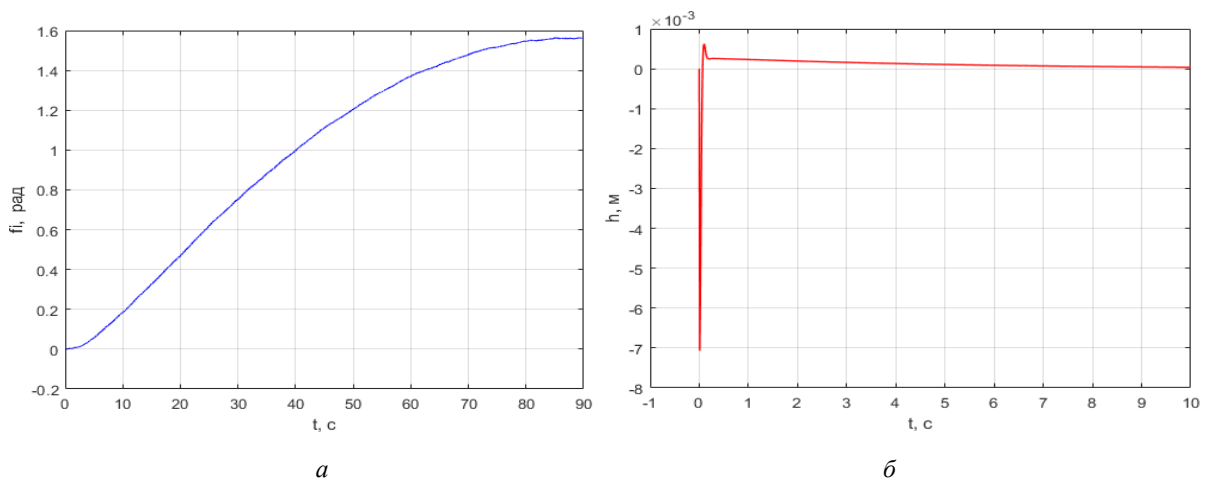


Рис. 3. Графики:  $a - \varphi(t)$ ;  $b - h(t)$

Fig. 3. Graphs:  $a - \varphi(t)$ ;  $b - h(t)$

The maximum deflection of the spoke  $h(t) = 7 \cdot 10^{-3}$  m is observed at the initial moment of time, thereafter, it smoothly tends to zero. When using the algorithm of sequential optimization according to the hierarchy of two target criteria, the stop and fixing mechanisms do not lead to additional oscillations of the unfolded antenna because of the smooth approach to the final state.

The optimal filtering and control algorithms successfully solve the problem under the selected perturbations and measurement noise. The deviations of the initial values of the variables can be chosen from the range  $\pm 7$  % of the maximum values of the corresponding quantities, otherwise the correction of the weighting coefficients is required.

Fig. 4,  $a$  shows a graph of the change in the estimation error  $\Delta\varphi$  at  $\mathbf{B}_z = \text{diag}(0,02, 0,0005)$  and in the absence of external disturbances. Fig. 4,  $b$  shows a similar curve when the intensity of  $\mathbf{B}_z$  is tripled. The largest error is reached at the beginning of the modelling, then it tends to zero (also for other  $\Delta\varphi(t_0)$ ). In the presence of external perturbations, the errors have a mathematical expectation equal to zero and a variance not exceeding the variance of the perturbations.

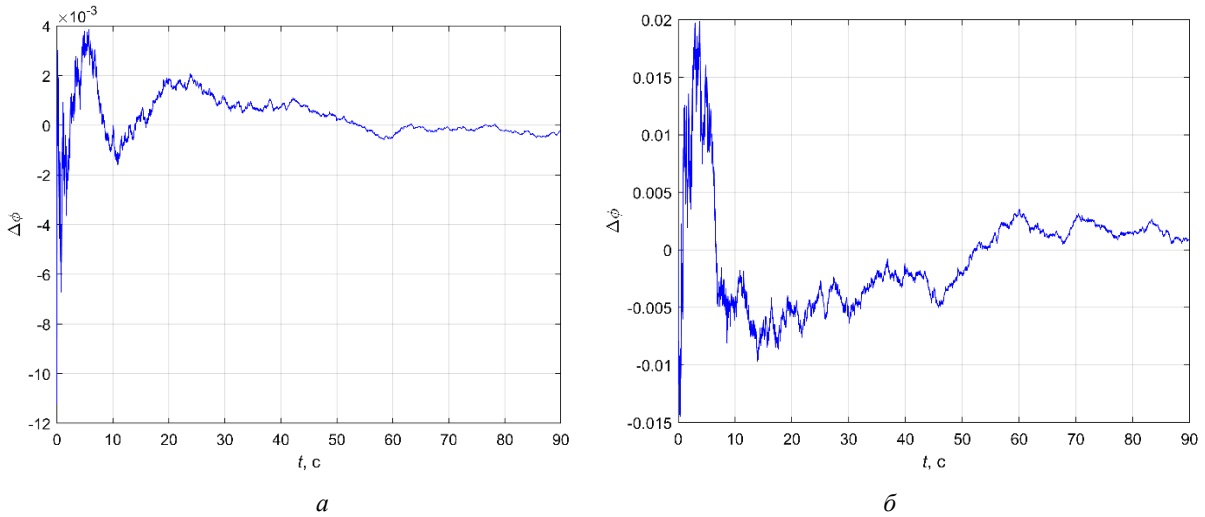


Рис. 4. Графики  $\Delta\varphi$  при различных уровнях интенсивности шума

Fig. 4. Graphs of  $\Delta\varphi$  at different levels of noise intensity

Fig. 5 shows the diagonal elements of the covariance matrix at  $R_{11}(0) = 0,017$ ;  $R_{22}(0) = 0,0002$ ;  $R_{33}(0) = 0,001$ ;  $R_{44}(0) = 0$ . Rather quickly they come to steady-state values. A simulation with different initial values of diagonal elements of the covariance matrix and different intensity of noise measurements was performed, and the Kalman filter successfully worked out for all variants.

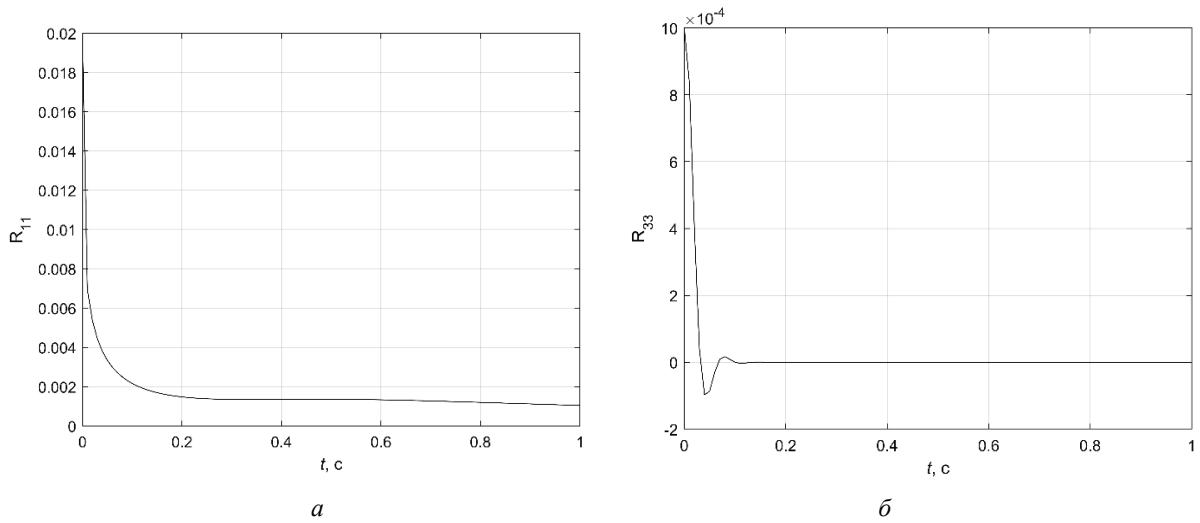


Рис. 5. Графики: а –  $R_{11}(t)$ ; б –  $R_{33}(t)$

Fig. 5. Graphs: а –  $R_{11}(t)$ ; б –  $R_{33}(t)$

To minimize energy costs, it was proposed to periodically turn off the operation of the sensors and to calculate the state estimation at these sections by predicting using equations (3), (4) at  $B_{z1}^{-1} = 0$  and  $B_{z2}^{-1} = 0$ . This made it possible to successfully solve the control problem at lower energy costs. When the sensors are turned off, no energy is expended for their operation and data transmission.

Fig. 6 shows a graph of  $R_{11}(t)$

$$\dot{R}_{11} = -R_{11}^2 B_{z1}^{-1} - R_{13}^2 b_1 B_{z2}^{-1} + 2R_{12} + B_{x1}$$

with periodic disconnection of measurements from the sensors. Each time the measurements are switched on, the elements of the covariance matrix reach a steady-state value. In the equation for  $\dot{R}_{11}$



the summands  $R_{11}^2 B_{z1}^{-1}$  and  $R_{13}^2 b_1 B_{z2}^{-1}$  characterize the rate of arrival of information, their absence when the measurements are switched off leads to the increase of  $R_{11}$ .

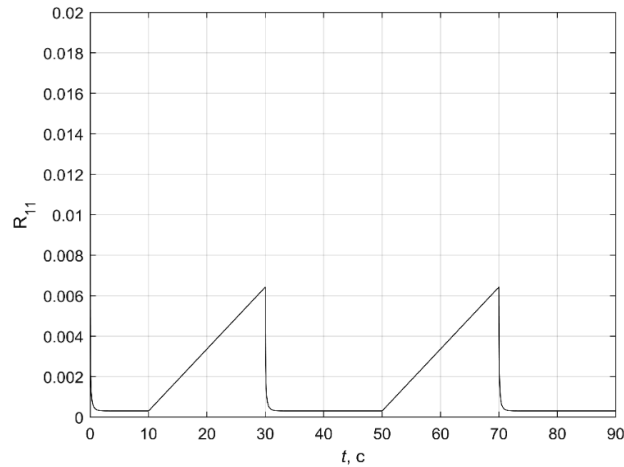


Рис. 6. График  $R_{11}(t)$

Fig. 6. Graph  $R_{11}(t)$

For successful solution of the problem and accurate fulfillment of the terminal conditions it is necessary to switch on the sensors measuring the state of the system at the final section of the optimization interval. The longer the sensor inclusion time at the end of the simulation, the more accurately the problem can be solved. Determining the optimal interval for switching on measurements is an independent scientific and technical task. If the intensity of external disturbances  $\mathbf{B}_x$  increases, it is necessary to measure the system state for a longer time. At a given  $\mathbf{B}_x = \text{diag}(0,02, 0, 0,0001, 0)$  for successful solution of the problem it is enough to switch on sensors in the period from 85 to 90 sec. If the disturbance values are doubled, it is necessary to increase the observation time in the final section to 15 s. Sensor operation time depends on type and intensity of external disturbances, requirements to permissible energy consumption value. As a result of statistical modeling the estimation of mathematical expectation of criterion (5) is  $M(J_1) = 0$ , criterion (6)  $M(J_2) = 0,035$ , where for one of the variants the following value  $\varphi(t_f) = 1.576$  is obtained.

A separate task is to determine the switching off time of the sensors measuring the angular position of the spoke and the deflection value independently of each other. Thus, in order to fulfill the terminal condition for the angle  $\varphi$  for a given perturbation, it is necessary to observe the last 5 s of the simulation, whereas for the deflection  $h$ , 3 s of observation are sufficient. The values of  $\varphi$  and  $h$  depend on the applied moment  $M$ . The value of  $h$  at the end of the opening with the selected control does not exceed  $5 \cdot 10^{-5}$  m, which corresponds to the accuracy of the sensor. Therefore, the value of the deflection at the final moment can be neglected.

### Conclusion

As a result of this work, the solution of the problem of optimal control of the stochastic LTR spoke opening model by incomplete data using the separation principle was confirmed. Using a sequential optimization algorithm with the data estimated using the Kalman filter allowed us to solve the problem under different intensities of disturbances and measurement noise. The interval switching off of measurements allows to reduce the energy consumption for sensor powering and measurement processing. Further work involves setting and solving the problem of optimizing the observation intervals to minimize the energy costs [23].

The presented research was reported at the XXII International Scientific Conference «System Analysis, Control and Navigation» [24].

## References

1. Puig L., Barton A., Rando N. A review on large deployable structures for astrophysics missions. *Acta Astronautica*. 2019, Vol. 67(1), P. 12–26.
2. Polyanskij I. S., Arhipov N. S., Misyurin S. Y. [On the solution of the problem of optimal control of an adaptive multi-beam reflector antenna]. *Avtomat. i telemekh.* 2019, No. 1, P. 83–100 (In Russ.).
3. Vlasov A. Y., Amel'chenko N. A., Pasechnik K. A., Titov M. A., Serzhantova M. V. [Static and modal analysis of the power construction of the precision large-sized antenna reflector from polymer composite materials]. *Siberian Journal of Science and Technology*. 2017, No. 4, P. 897–901 (In Russ.).
4. Nie R., He B., Zhang L. Deployment dynamics modeling and analysis for mesh reflector antennas considering the motion feasibility. *Nonlinear Dyn.* 2018, Vol. 91, P. 549–564.
5. Thomson M. W. The AstroMesh Deployable Reflector. *IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*. 2000, P. 435–446.
6. Li P., Liu C., Tian Q., Hu H., Song Y. Dynamics of a deployable mesh reflector of satellite antenna: form finding and modal analysis. *J Comput. Nonlinear Dyn.* 2016, Vol. 11(4), P. 549–564.
7. Reznik S. V., Chubanov D. E. [Large-sized transformable space antenna reflector made of composite materials dynamic modeling process]. *RUDN Journal of Engineering Researches*. 2018, Vol. 19(4), P. 411–425 (In Russ.).
8. Bakulin V. N., Borzyh S. V. [Modeling the dynamics of the process of deployment large-sized transformable space structures]. *Izvestiya vysshih uchebnyh zavedenij. Aviacionnaya tekhnika*. 2020, No. 4, P. 50–56 (In Russ.).
9. Berns V. A., Levin V. E., Krasnorutsky D. A., Marinin D. A., Zhukov E. P., Malenkova V. V., Lakiza P. A. [Development of a calculation and experimental method for modal analysis of large transformable space structures]. *Spacecrafts & Technologies*. 2018, Vol. 2, No. 3, P. 125–133 (In Russ.).
10. Kabanov S. A., Zimin B. A., Mitin F. V. [Development and Research of Mathematical Models of Deployment of Mobile Parts of Transformable Space Construction. Part I]. *Mekhatronika, Avtomatizatsiya, Upravlenie*. 2020, Vol. 21, No. 1, P. 51–64 (In Russ.).
11. Kabanov S. A., Mitin F. V. Optimization of the stages of deploying a large-sized space-based reflector. *Acta Astronautica, Special Issue on 6th SFS 2019*. 2020, 176, P. 717–724.
12. Huang H., Cheng Q., Zheng L., Yang Y. Development for petal-type deployable solid-surface reflector by uniaxial rotation mechanism. *Acta Astronautica*. 2021, No. 178, P. 511–521.
13. Ishkov V. N. [Solar geoeffective phenomena: Action on the near-earth outer space and the possibility of the forecast]. *Slozhnye sistemy*. 2012, No. 4 (5), P. 21–41 (In Russ.).
14. Mihalyaev B. B., Derteev S. B., Lagaev I. Y., Osmonov T. T. [Vliyanie solnechnoj aktivnosti na magnitosferu Zemli]. *V sbornike: Aktual'nye problemy sovremennoj fiziki i matematiki. trudy*. 2017, P. 92–97 (In Russ.).
15. Kabanov S. A., Mitin F. V. Optimization of the Processes of Deployment and Shape Generation for a Transformable Space-Based Reflector. *Journal of Computer and Systems Sciences International*. 2021, Vol. 60, No. 2, P. 283–302.
16. Kabanov S. A., Kabanov D. S. [Deployment the Spoke of a Large-Sized Transformable Reflector Using a Sequential Optimization Algorithm]. *Mekhatronika, Avtomatizatsiya, Upravlenie*. 2021, Vol. 22(8), P. 433–441 (In Russ.).
17. *Spravochnik po teorii avtomaticheskogo upravleniya. Pod red. A. A. Krasovskogo* [Handbook on the theory of automatic control. Ed. by A. A. Krasovskij]. Moscow, Nauka Publ., 1987, 712 p.
18. Kabanov S. A. *Optimizatsiya dinamiki sistem pri dejstvii vozmushchenij* [Optimization of the dynamics of systems under the action of disturbances]. Moscow, Fizmatlit Publ., 2008, 200 p.
19. Kabanov D. S. [Optimal control of a nuclear reactor taking into account random disturbances]. *Journal of instrument engineering*. 2009, No. 5, P. 27–30 (In Russ.).

20. *Mikroprivod* [Microdrive]. Available at: <http://www.microprivod.ru/catalog/phytron/seriya-ssspspace-dlya-raboty-v-kosmose,diametr-19-125-mm.html> (accessed: 10.10.2021).
21. *Pinter-Plotter.ru* [Pinter Plotter.ru]. Available at: <https://printer-plotter.ru/3d-oborudovanie/3d-scanners/rangevision/?yclid=5975775935832053836> (accessed: 10.10.2021).
22. *SKB IS* [SKB IS]. Available at: <http://www.skbis.ru/index.php?p=3&c=18&d=128> (accessed: 10.10.2021).
23. Malyshev V. V., Krasil'shchikov M. N., Karlov V. I. *Optimizaciya nablyudeniya i upravleniya letatel'nyh apparatov* [Optimization of surveillance and control of aircraft]. Moscow, Mashinostroenie Publ., 1989, 312 p.
24. Kabanov S. A., Kabanov D. S., Nikulin E. N., Mitin F. V. [Optimal control of deployment of the spoke of a transformable reflector in the presence of disturbance]. *Sistemnyj analiz, upravlenie i navigaciya: Tezisy dokladov*. Moscow, Izd-vo MAI Publ., 2021, P. 168–169.

### Библиографические ссылки

1. Puig, L., Barton, A., Rando, N. A review on large deployable structures for astrophysics missions. *Acta Astronautica*. 2019. Vol. 67(1). P. 12–26.
2. Полянский И. С., Архипов Н. С., Мисюрин С. Ю. О решении проблемы оптимального управления адаптивной многолучевой зеркальной антенной // *Автомат. и телемех.* 2019. № 1. С. 83–100.
3. Статический и модальный анализ силовой конструкции прецизионного крупногабаритного антенного рефлектора из полимерных композиционных материалов / А. Ю. Власов, Н. А. Амельченко, К. А. Пасечник и др. // *Сибирский журнал науки и технологий.* 2017. № 4. С. 897–901.
4. Nie R., He B., Zhang L. Deployment dynamics modeling and analysis for mesh reflector antennas considering the motion feasibility // *Nonlinear Dyn.* 2018. Vol. 91. P. 549–564.
5. Thomson M. W. The AstroMesh Deployable Reflector. IUTAM-IASS Symposium on Deployable Structures: Theory and Applications. 2000. P. 435–446.
6. Dynamics of a deployable mesh reflector of satellite antenna: form finding and modal analysis / P. Li, C. Liu, Q. Tian // *J Comput. Nonlinear Dyn.* 2016. Vol. 11(4). P. 549–564.
7. Резник С. В., Чубанов Д. Е. Моделирование динамики раскрытия крупногабаритного трансформируемого рефлектора космической антенны из композиционного материала // *Вестник Рос. ун-та дружбы народов. Серия: Инженерные исследования.* 2018. Т. 19, № 4. С. 411–425.
8. Бакулин В. Н., Борзых С. В. Моделирование динамики процесса раскрытия крупногабаритных трансформируемых космических конструкций // *Изв. высш. учебн. завед. Авиационная техника.* 2020. № 4. С. 50–56.
9. Разработка расчетно-экспериментального метода модального анализа / В. А. Бернс, В. Е. Левин, Д. А. Красноруцкий и др. // *Космические аппараты и технологии.* 2018. Т. 2, № 3(25). С. 125–133.
10. Кabanov S. A., Зимин Б. А., Митин Ф. В. Разработка и анализ математических моделей раскрытия подвижных частей трансформируемых космических конструкций. Ч. I // *Мехатроника, автоматизация, управление.* 2020. Т. 20, № 1. С. 51–64.
11. Kabanov S. A., Mitin F. V. Optimization of the stages of deploying a large-sized space-based reflector // *Acta Astronautica, Special Issue on 6th SFS 2019.* 2020. Vol. 176. P. 717–724.
12. Development for petal-type deployable solid-surface reflector by uniaxial rotation mechanism / H. Huang, Q. Cheng, L. Zheng, Y. Yang // *Acta Astronautica.* 2021. No. 178. P. 511–521.
13. Ишков В. Н. Воздействие солнечных активных явлений на околоземное космическое пространство и возможность их прогноза // *Сложные системы.* 2012. № 4 (5). С. 21–41.

14. Влияние солнечной активности на магнитосферу Земли / Б. Б. Михалеев, С. Б. Дертеев, И. Ю. Лагаев, Т. Т. Осмонов // Актуальные проблемы современной физики и математики. 2017. С. 92–97.
  15. Кабанов С. А., Митин Ф. В. Оптимизация процессов раскрытия и создания формы трансформируемого рефлектора космического базирования // Изв. РАН. ТиСУ. 2021. № 2. С. 106–125.
  16. Кабанов С. А., Кабанов Д. С. Управление разведением спиц крупногабаритного трансформируемого рефлектора с использованием алгоритма последовательной оптимизации // Мехатроника, автоматизация, управление. 2021. № 22(8). С. 433–441.
  17. Справочник по теории автоматического управления / под ред. А. А. Красовского. М. : Наука, 1987. 712 с.
  18. Кабанов С. А. Оптимизация динамики систем при действии возмущений. М. : Физматлит, 2008. 200 с.
  19. Кабанов Д. С. Оптимальное управление ядерным реактором с учетом случайных возмущений // Приборостроение. 2009. № 5. С. 27–30.
  20. Микропривод [Электронный ресурс]. URL: <http://www.microprivod.ru/catalog/phytron/seriya-vssspase-dlya-raboty-i-v-kosmose,diametr-19-125-mm.html> (дата обращения 10.10.2021).
  21. Пинтер-Плоттер.ру [Электронный ресурс]. URL: <https://printer-plotter.ru/3d-oborudovanie/3d-scanners/rangevision/?yclid=5975775935832053836> (дата обращения 10.10.2021).
  22. СКБ ИС [Электронный ресурс]. URL: <http://www.skbis.ru/index.php?p=3&c=18&d=128> (дата обращения 10.10.2021).
  23. Малышев В. В., Красильщиков М. Н., Карлов В. И. Оптимизация наблюдения и управления летательных аппаратов. М. : Машиностроение, 1989. 312 с.
- Оптимальное управление разведением спицы трансформируемого рефлектора при наличии возмущений / С. А. Кабанов, Д. С. Кабанов, Е. Н. Никулин, Ф. В. Митин // Системный анализ, управление и навигация : тез. докладов. М. : Изд-во МАИ, 2021. С. 168–169.

© Kabanov S. A., Kabanov D. S., Nikulin E. N., Mitin F. V., 2021

---

**Кабанов Сергей Александрович** – доктор технических наук, профессор кафедры систем управления и компьютерных технологий; БГТУ «ВОЕНМЕХ» им. Д. Ф. Устинова. E-mail: kaba-sa@mail.ru.

**Кабанов Дмитрий Сергеевич** – кандидат технических наук, научный сотрудник; НИЛ РИУС БГТУ «ВОЕНМЕХ» им. Д. Ф. Устинова. E-mail: kabanovds@mail.ru.

**Никулин Евгений Николаевич** – доктор технических наук, профессор, заместитель директора Института систем вооружения; БГТУ «ВОЕНМЕХ» им. Д. Ф. Устинова. E-mail: nikulin\_en@voenmeh.ru.

**Митин Фёдор Васильевич** – кандидат технических наук, доцент кафедры систем управления и компьютерных технологий; БГТУ «ВОЕНМЕХ» им. Д. Ф. Устинова. E-mail: fedor28@list.ru.

**Kabanov Sergey Aleksandrovich** – Dr. Sc., Professor; Department of Control Systems and Computer Technologies, Baltic State Technical University “VOENMEH” named after D. F. Ustinov. E-mail: kaba-sa@mail.ru.

**Kabanov Dmitriy Sergeevich** – Cand. Sc., researcher, NIL RIUS; Baltic State Technical University “VOENMEH” named after D. F. Ustinov. E-mail: kabanovds@mail.ru.

**Nikulin Evgeniy Nikolaevich** – Dr. Sc., Professor, Deputy Director of the Institute of Weapon Systems; Baltic State Technical University “VOENMEH” named after D. F. Ustinov. E-mail: nikulin\_en@voenmeh.ru.

**Mitin Fedor Vasilyevich** – Cand. Sc., Associate Professor, Department of Control Systems and Computer Technologies; Baltic State Technical University “VOENMEH” named after D. F. Ustinov. E-mail: fedor28@list.ru.

---