Предложенные транспортные роботы могут использоваться как для транспортировки отдельных частей ракетной техники в пределах монтажно-испытательного комплекса при сборке, так и для доставки ракет-носителей на стартовый стол. Это позволит удешевить и ускорить сооружение транспортной сети ракетного наземного комплекса.

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ATTITUDE DETERMINATION, CONTROL AND STABILIZATION OF A NANOSATELLITE USING REACTION WHEELS

Дніпропетровський національний університет імені Олеся Гончара разом з іншими університетами України розробляє університетський наносупутник УМС-1, призначений для отримання зображень земної поверхні. Для виконання цільової задачі необхідно забезпечення кутової орієнтації супутника. Розглядається питання синтезу системи орієнтації і вибору параметрів приводу з використанням двигунів-маховиків, наводяться результати моделювання.
***Ключові слова*: наносупутник, управління кутовим положенням, двигун-маховик.**

Dnepropetrovsk National University is developing a nanosatellite with others institutions of Ukraine, the УМС-1. This satellite will be use for imagery. For accomplishing this mission it is necessary to provide attitude control of the satellite. The problems of synthesis of the attitude control system and choice of parameters of actuators with the use of reaction wheels are considered, the simulation outcomes are shown.
***Key words*: nanosatellite, attitude control, reaction wheel.**

Днепропетровский национальный университет имени Олеся Гончара совместно с другими университетами Украины разрабатывает университетский наноспут-

ник УМС-1, предназначенный для получения изображений земной поверхности. Для выполнения целевой задачи необходимо обеспечение угловой ориентации спутника. Рассматривается вопрос синтеза системы ориентации и выбора параметров привода с использованием двигателей-маховиков, приводятся результаты моделирования.

Ключевые слова: наноспутник, управление угловым положением, двигатель-маховик.

Problem Description

The УМС-1 nanosatellite is been developed by Dnipropetrovsk National University (ДНУ), Kyiv Polytechnic Institute (КПИ), Kharkiv Aviation Institute (ХАИ) and by Kharkiv National University of Radio Electronics (ХНУРЭ). This satellite will be used for imagery and is intended to be used to train many students of these institutions.

The УМС-1 nanosatellite will have mass about 10kg, dimensions of 150 × 150 × 400 mm and will have 4 solar panels to recharge its batteries. Hence the system may have a mean power consumption of 7W in one day. Figure 1 shows a 3D modeling of how it should looks like after built.

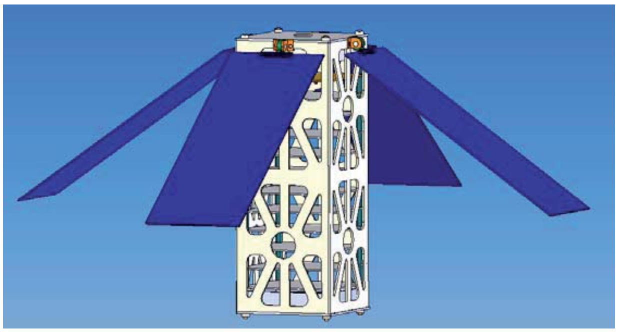

Fig. 1. 3D model of the nanosatellite УМС-1

To accomplish the task of taking photos of the Earth's surface, the satellite must be 3-axis stabilized. This means that it will be able to point to the Earth with null angular rates in all of its axes. To do this the satellite needs an attitude determination and control systems (ADCS). This system determines the actual attitude of the satellite and changes it to the referenced one. This paper presents the design of one ADCS for the nanosatellite УМС-1.

Problem Solution

The УМС-1 will have two ADCS. One of them (Electromagnetic ADCS) comprises electromagnetic actuators and magnetometers, sun sensors, GPS and gyrometers as sensors. In turn, the other system (Mechanical ADCS) comprises reaction wheels as actuators and a star tracker as sensor. This paper shows the design of the mechanical ADCS. A block diagram representing the simulated system is depicted in Figure 2.

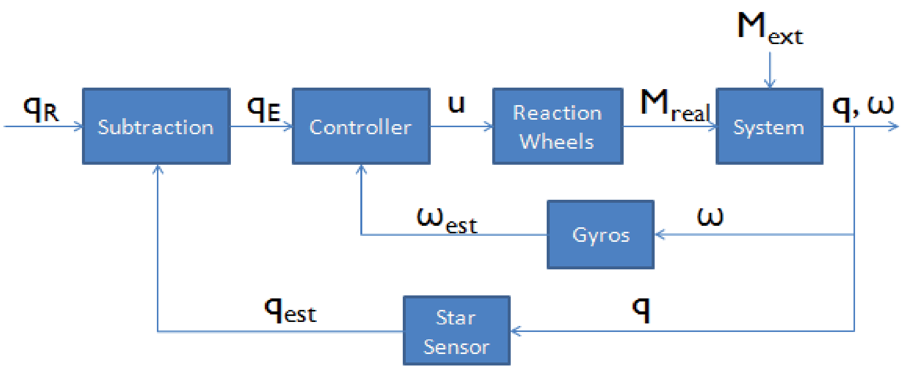

Fig. 2. Block diagram of the mechanical ADCS for simulation

In Figure 2 q_R is the reference quaternion, q_E is the quaternion error, u is the control signal, M_{EXT} is the sum of all external torque which disturb the system, M_{REAL} is the real torque applied to the system, q is the real attitude of the satellite, ω is the angular rate of the satellite, q_{EST} is the attitude estimated by the star tracker and ω_{EST} is the angular rate estimated by the gyrometers of the electromagnetic ADCS.

The attitude representation is made by quaternions, which are hyper-complexes numbers of rank 4 represented by the sum of a scalar with a three-dimension vector, as illustrated by equation (1). Reference [1] presents a wide explanation about quaternion algebra.

$$q = q_1 i + q_2 j + q_3 k + q_4 , \tag{1}$$

where i, j and k stand for the standard orthonormal base of R^3, q_1, q_2 and q_3 are the projections of the vector in this base and q_4 is the scalar.

The *Subtraction* block calculates the quaternion error based on the estimated attitude quaternion and on the attitude reference. References [2,3] show that the quaternion error can be obtained by equation (2).

$$q_E = q_{EST}^{-1} \cdot q_R = \begin{pmatrix} q_{R4} & q_{R3} & -q_{R2} & q_{R1} \\ -q_{R3} & q_{R4} & q_{R1} & q_{R2} \\ q_{R2} & -q_{R1} & q_{R4} & q_{R3} \\ -q_{R1} & -q_{R2} & -q_{R3} & q_{R4} \end{pmatrix} \cdot \begin{pmatrix} -q_{EST1} \\ -q_{EST2} \\ -q_{EST3} \\ q_{EST4} \end{pmatrix} . \tag{2}$$

With the error calculated, the *Controller* block calculates the control torque M_C and sends it as a control signal u to the internal controller of the reaction wheels. Reference [2] shows the equation of the proportional-derivative controller (3).

$$M_C = k_P \Phi_E + k_D \Phi'_E , \tag{3}$$

where M_C is the control torque, k_P is the gain proportional to the error Φ_E, k_D is the gain proportional to the angular rate error Φ'_E. These gains can be adjusted by simulations.

Using quaternion representation, equation (3) turns into equations (4):

$$M_{CX} = 2k_{PX} q_{E1} q_{E4} + k_{DX} \omega_{EX} , \tag{4a}$$

$$M_{CY} = 2k_{PY} q_{E2} q_{E4} + k_{DY} \omega_{EY} , \tag{4b}$$

$$M_{CZ} = 2k_{PZ} q_{E3} q_{E4} + k_{DZ} \omega_{EZ} . \tag{4c}$$

The *Reaction Wheels* block receives the control signal u, which is the reference torque for the internal controller, and controls the wheels to achieve this torque. It also saturates the output torque, considering the maximum torque and maximum angular momentum. The result is the real torque applied to the satellite.

For this block commercial reaction wheels were compared so the parameters needed for simulation could be obtained. Table 1 shows the most relevant commercial reaction wheels considered.

Table 1

Commercial reaction wheels for nanosatellites

	MAI-101	Sinclair RW-0.03	AstroFein RW35
Size	76.2 × 76.2 × 69.85 mm	50 × 50 × 40 mm	95 × 95 × 40 mm
Mass	620 g	185 g	500 g
Torque	< 0.635 mNm	2 mNm	5 mNm
Momentum	1.1 mNms	30 mNms	100 mNms
Power Consumption	< 10 W	< 1.5 W	< 5W
Number of Wheels	3	1	1

Considering size, MAI-101 is the best choice. However it is not very powerful, consumes much power and, for УМС-1, it can only control initial angular rates up to

0,4º/s. So the chosen reaction wheel is Sinclair RW-0.03. It is enough powerful, not very big and consumes less power than MAI-101.

The *System* block uses two models to determine how the attitude and the angular rate evolve with time. According to [4], the kinematical model describes the time evolution of the attitude, while the dynamical model describes the time evolution of the angular rate. Equations (5), (6), (7) and (8) show these models:

$$\frac{dq(t)}{dt} = \frac{1}{2}\Omega q(t), \tag{5}$$

$$\Omega = \begin{pmatrix} 0 & \omega_Z & -\omega_Y & \omega_X \\ -\omega_Z & 0 & \omega_X & \omega_Y \\ \omega_Y & -\omega_X & 0 & \omega_Z \\ -\omega_X & -\omega_Y & -\omega_Z & 0 \end{pmatrix}, \tag{6}$$

$$J\frac{\partial \omega(t)}{\partial t} + S(\omega(t))J\omega(t) = M, \tag{7}$$

$$S(\omega(t)) = \begin{pmatrix} 0 & -\omega_Z & \omega_Y \\ \omega_Z & 0 & -\omega_X \\ -\omega_Y & \omega_X & 0 \end{pmatrix}. \tag{8}$$

In equation (7), M is the sum of the real torque applied by the reaction wheels M_{REAL} and the external torques M_{EXT} and J is the inertia tensor given by equation (9):

$$J = \begin{pmatrix} \int(y^2+z^2)dm & -\int(xy)dm & -\int(xz)dm \\ -\int(xy)dm & \int(x^2+z^2)dm & -\int(yz)dm \\ -\int(xz)dm & -\int(yz)dm & \int(x^2+y^2)dm \end{pmatrix}. \tag{9}$$

For the simulations made in this paper, the inertia tensor was calculated for a homogenous block with dimensions 150 × 150 × 400 mm and mass of 10 kg. The resulting matrix is shown in equation (10):

$$J = \begin{pmatrix} 0.1521 & 0 & 0 \\ 0 & 0.1521 & 0 \\ 0 & 0 & 0.00375 \end{pmatrix}. \tag{10}$$

As J is a diagonal matrix, the equations (7) and (8) are simplified to equations (11):

$$J_X\frac{\partial \omega_X}{\partial t} + \omega_Y\omega_Z(J_Z - J_Y) = M_X, \tag{11a}$$

$$J_Y\frac{\partial \omega_Y}{\partial t} + \omega_X\omega_Z(J_X - J_Z) = M_Y, \tag{11b}$$

$$J_Z\frac{\partial \omega_Z}{\partial t} + \omega_X\omega_Y(J_Y - J_X) = M_Z. \tag{11c}$$

The *Gyros* block represents the gyrometers from the electromagnetic ADCS. For the simulations of this work, the gyrometers are considered ideal in some cases and are considered not available in other cases. In the first configuration, the estimated angular rate is identical to the real one. In the second case, the angular rate may be obtained by differentiation of the attitude. As quaternions are used in this work, this can be done by equation (12), according to [2]:

$$\omega = 2Q\frac{dq(t)}{dt}, \tag{12}$$

where

$$Q = \begin{pmatrix} q_4 & q_3 & -q_2 & -q_1 \\ -q_3 & q_4 & q_1 & -q_2 \\ q_2 & -q_1 & q_4 & -q_3 \end{pmatrix}. \tag{13}$$

The *Star Sensor* block applies noise to the real attitude according to the selected sensor. Table 2 shows the most relevant commercial star trackers considered for this work.

Table 2

Commercial star trackers for nanosatellites

	Sinclair S3S	Comtech MST
Size	59 × 56 × 32.5 mm	60 × 76.2 × 76.2 mm
Mass	90 g	375 g
Accuracy	36 arcsec attitude with 85% confidence	X,Y<70 arcsec, Z<150 arcsec
Power Comsumption	< 1.0 W	< 2.0 W

In the case of the star tracker, size should not be a big problem because it is going to be placed outside the satellite. Sinclair S3S has better characteristics than the Comtech MST. Hence Sinclair S3S was chosen.

Described all the blocks of Figure 2, the simulations were made. The first three simulations considered the gyrometers ideal. Hence the steady-state signal will oscillate into the interval given by the error of the star tracker, in this case ± 0,01º. The first one considers the case where the satellite presents an initial angular position error of 90º in one of the angles. Table 3 shows the setting times for the controllers with $k_P = 1$ and $k_D =$ 0,5, $k_D = 1$, $k_D = 4$, $k_D = 5$, $k_D = 6$ and $k_D = 7$.

Table 3

Setting times for the first simulation

K_d	0.5	1	4	5	6	7
Setting Time (s)	246.44	123.65	54.05	44.12	61.71	70.29

In this first simulation it is possible to see that for $k_D = 5$ the system was faster than for the other cases. For this gain, the response was close to the critically-dumped one, hence the small setting time.

In the second simulation the satellite is already in the desired position, but with an initial angular rate of 2º/s. Table 4 shows the setting times.

Table 4

Setting times for the second simulation

K_d	0.5	1	4	5	6	7
Setting Time (s)	10.69	7.07	25.27	30.65	36.30	41.87

In this case, the fastest response was with gain $k_D = 1$. This simulation showed that this ADCS could control angular rate errors. However, the final controller could not be found, because different values of k_D were found. Hence a third simulation is needed.

In the third simulation both initial angle position error and initial angular rate error were considered. Table 5 shows the setting times for this case.

Table 5

Setting times for the third simulation

K_d	0.5	1	4	5	6	7
Setting Time (s)	256.14	129.94	48.43	31.30	50.74	57.24

In this simulation, the response for $k_D = 5$ was the closest to the critically-dumped one, as in the first simulation. Hence this is considered to be the final controller.

A fourth simulation was made with the same conditions of the third one, but the gyrometers are considered not available and the angular rates were calculated by equation (12). Figures 3, 4 and 5 show the time responses of the controllers.

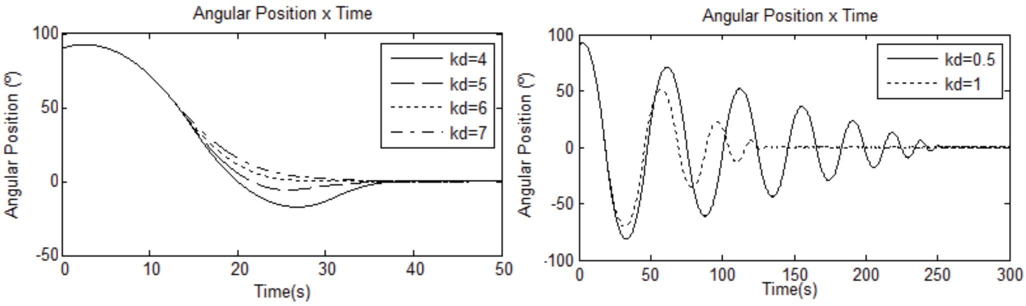

Fig. 3. Simulation of Angular Position x Time for initial position of 90°, initial angular rate of 2°/s and without gyrometers

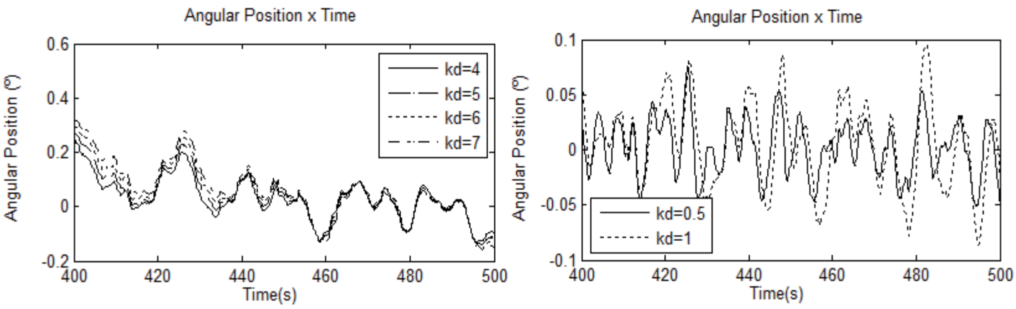

Fig. 4. Steady-state responses of the signals depicted in Figure 3

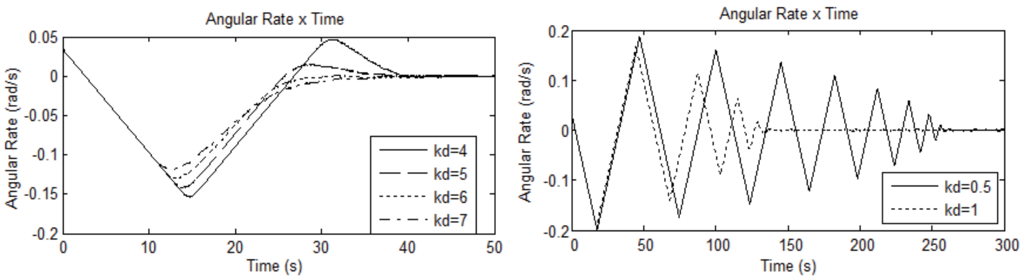

Fig. 5. Simulation of Angular Rate x Time for initial position of 90°, initial angular rate of 2°/s and without gyrometers

In Figure 3, it is possible to see that the calculation of the angular rates by the derivative of the position turned response for $k_D = 5$ into an under-damped one. It also can be seen that until about 10s all the signals have the same response, which may be caused by the saturation of the actuators. Comparing both graphs, it can be seen that, for a small derivative gain k_D the system has a very under-damped response, which leads to a large setting time.

Figure 4 depicts the steady-state response for all six gains. In this Figure it is possible to see that, the smaller the derivative gain, the smaller are the steady-state oscillations.

In Figure 5, it is possible to see by the straight lines that indeed actuators saturated. This is because the actuation signal is the torque, which is proportional to the derivative of the angular rates. This shows that the system might be consuming more power than the power available. Hence this system should not be turned on all the time.

Unlike the results for the third simulation, Table 6 shows that the fastest response was for $k_D = 6$. Hence the controller with $k_D = 5$ can be used when gyrometers are available. However the derivative gain should be changed to $k_D = 6$ if there is a failure in these sensors or if they are not available.

Table 6 shows time instants when the response was confined into the interval of ± 0,3º because the signal oscillated into it, as shown in Figure 4.

Table 6

Setting times for the fourth simulation

K_d	0.5	1	4	5	6	7
Setting Time (s)	256.02	133.39	36.96	35.86	27.37	35.75

Conclusions and Future Works

This paper proposes an ADCS for the УМС-1 nanosatellite. This system has three reaction wheels as actuators and a star tracker as sensor. The hardware was already been chosen and some simulations were made. In the first simulation, it was studied the case where the ADCS must control an initial position error. In the second, there is only an initial angular rate error. In the third, there are both initial errors. At last, the fourth simulation was made without measurements of angular rates.

The designed ADCS could satisfactory control the satellite, but it might consume much power and should not be turned on all the time. This system may be used to reach the target attitude and then the electromagnetic one may maintain the attitude while pictures are not made, since it consumes less power. Also, both systems must work together when the reaction wheels reach a very high rotation speed and need to be unloaded.

This paper presents only the preliminary ADCS. For future works, estimation filters should be tested and compared to improve the attitude determination. Moreover some other controllers should also be implemented and compared.

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