PD adaptive controller method for a three-axis stabilized rigid satellite attitude system

J. E Benmansour[(1)*], E. Benfriha[(1)], A. Bellar [(1)]
[(1)] Département de Recherche en Mécanique Spatiale Centre de Développement des Satellites (CDS) Oran, Algeria

*jebenmansour@cds.asal.dz

Abstract: This paper deals with the attitude tracking control problem of rigid satellite with uncertainties of disturbances. An adaptive proportional derivative controller (PD) is proposed to deal with the influence of external disturbance in the attitude controller. The uncertain disturbances can be estimated through an adaptive algorithm and can be compensated in the proposed controller. The tracking error and the closed-loop system stability are ensured based on the Lyapunov analysis using the representation of the spacecraft dynamics especially the quaternion properties. Simulation results can clearly illustrate the feasibility, the effectiveness and the performance of the planned control strategies, which have been validated by the Monte Carlo method, the results can be extended to other adaptive attitude control laws.

Keywords: Attitude control, Rigid spacecraft, uncertain Disturbances, Adaptive algorithm, PD controller.

1. INTRODUCTION

The problem attitude control of satellite is largelyposed in the space missions, a number of solutions have been proposed for the adequate treatment of such problem [1-3]. However, Space missions are generally performed under different space environments and subject to various disturbances, for instance: aerodynamic torque, gravitational torque, radiation torque [4], these disturbances have a direct influence on the control performance, particularly in the case of LEO satellites operating in the altitude ranges where their dynamics are significantly affected by most of the aforementioned disturbances.

Hence, attitude control of such satellites becomes a challenging task in order to deal with uncertain disturbances problem that requires an attitude control with high tracking precession, high pointing accuracy and high stability, for this reason, it is necessary to find an efficient control method, which deals with the disturbance problem. Many works are oriented towards the spacecraft attitude control issue through external disturbance where various control approaches have been proposed to treat this problem such as : the PID controller [5], optimal control [6-8], sliding mode control [9-11]. Furthermore, the approach of adaptive control is proposed as a solution against the problem of the complex variant dynamics (uncertain), for this reason, the adaptive control is more used in aerospace domain to overcome the problems of uncertainties of the inertia matrix and environmental disturbances.

The control technique proposed for the International Space Station (ISS) is based on an adaptive controller [12] in which the spacecraft was considered as a rigid body, the controller is constructed by incorporating a planned adaptation attitude gains in order to have an attitude tracking with an acceptable performance.. Otherwise, to address the control issue of a rigid attitude satellite under external disturbances with inertia matrix uncertainty, the optimal inverse theory using the method of adaptive control were employed [13]. In addition, to overcome the uncertainties of the parameter and robust performance tracking, an adaptive PID controller has been discussed in [14] by integrating the fuzzy logic system with sliding mode controller. Two LQR designs based on two different models, the reduced quaternion and the Euler angle model, are conducted in [15], this strategy show that the reduced quaternion for attitude control systems in orbit-raising mode is a promising technique

The problem of adaptive output feedback control for satellite proximity operations has been studied in [16] this approach has shown an improvement in monitoring results and robustness under various conditions compared to the PD controller, the adaptive control based on robust observer is applied to rigid spacecraft in [17]. A sliding mode adaptive control mode was emplyed in [18] where the spacecraft is treated as a rigid body, the controller consist of an adaptive algorithm for disturbances estimation which will be suppressed there after using the controller based on the sliding surface.

It is noteworthy that in the previous adaptive control methods, the controllers consist of two (or more) combining control techniques which increase the system complexity. Thus, the reliability will be decreased that represents an important problem in the space domain, therefore, it is required to think of the simplistic way of an attitude tracking control with a low complexity degree without decreasing the control performance.

In the present paper, a PD adaptive attitude controller is applied to rigid spacecraft to deal with external disturbances uncertainties effect on the control performances. The proposed controller consists in estimating the external disturbances uncertainties and than in compensating them in order to get a best tracking control, high poniting accuracy and suitabale stability. The convergence of tracking error and the completed system stability are guaranteed using Lyapunov analysis method.

Finally, the aquired results can demonstrate the feasability and usefulness of the planned controller which can be extended to other adaptive attitude control laws and can be insert into the devlopped control methods of satellite tracking control under uncertain disturbances.

.

2. MODEL DESCRIPTION

A. Mathematical model of satellite attitude

There are principally two methods to define the attitude motion of the satellite. Euler angles and quaternions that can be combined to each other.

The kinematic and dynamic equations of satellite attitude can be described as follows [19]

$$J\dot{\omega} = -\omega^{\times} J\omega + u + d \quad (1)$$

$$\dot{q}_v = \frac{1}{2}\left(q_v^{\times} + q_0 I_3\right)\omega \quad (2)$$

$$\dot{q}_0 = -\frac{1}{2} q_v^{\,T}\omega \quad (3)$$

where $J \in R^3$ denotes the moment of inertia matrix which is constant and symmetric. $\omega = [\omega_1, \omega_2, \omega_3]^T$ denotes the angular velocity vector of body coordinate system relative to inertial coordinate system. u and d are respectively satellite's control forces and disturbances. I_3 Is three-unit matrix. q is the unit quaternion of satellite body coordinate system, $q = [q_0, q_v]^T$ with $q_v = [q_1, q_2, q_3]^T$. The interaction between them is:

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1 \quad (4)$$

$[a^{\times}]$ is an operator on any vector $a = [a_1, a_2, a_3]^T$ such that [20]:

$$[a^{\times}] = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \quad (5)$$

Let $q_e = [q_{ve}, q_{0e}]^T$ denotes the relative attitude error from a desired reference frame to the body-fixed reference frame of the satellite. Then we can have:

$$q_e = q \otimes q_d^{-1} \quad (6)$$

Where q_d^{-1} is the inversed desired quaternion and $\otimes$ is the quaternion multiplication operator. Therefore, the relative attitude error is obtained by:

$$\begin{bmatrix} \dot{q}_{ve} \\ \dot{q}_{0v} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} q_{0v} I_{3x3} + \left(q_{ve}^{\times}\right) \\ -q_{ve}^{\,T} \end{bmatrix}\omega_e(t) \quad (7)$$

and

$$\omega_e = \omega - \omega_d \quad (8)$$

Where ω_d represents the expected the satellite angular velocity, which is considered to be equal to zero, and thus $\omega_d = 0 \rightarrow \omega_e = \omega$.

Hence, the angular velocity of the spacecraft can be derived as below [21]:

$$\dot{\omega}_e = \dot{\omega} = -J^{-1}\left(\omega^{\times}\right)J\omega + J^{-1}u + J^{-1}d \quad (9)$$

The orbit of a small satellite, encompassing eccentricity, inclination, and altitude and the satellite in complex environments may be affected by aerodynamic moments d_p, gravity gradient moments d_g, geomagnetic moments d_m and solar pressure d_s [22]. The total environmental disturbance torque can be given as

$$d=d_p+d_g+d_m+d_s \quad (10)$$

These moments of external disturbance do not always exist and remain unchanged, but are related to the satellite orbit altitude, the distribution of the structure and the conditions of the space environment.

Assumption: the total disturbance torque d is bounded and is slow-varying, thus it is reasonable that $\dot{d}\approx 0$.

B. PD adaptive attitude controller

In this section, a PD adaptive attitude controller is designed, which can compensate the effect of the variation of the spacecraft's disturbances, for this purpose, we will show the controller law in form Eq. (11) which can stabilize the origin of the plant Eq. (1), Eq (2) and Eq. (3).

$$u=\omega^{\times}(J\omega)\text{-}D\omega\text{-}Kq\text{-}\hat{d} \quad (11)$$

where $\hat{d}$ is the estimated disturbance of d, which can be defined using an adaptive law as fellow:

$$\hat{d}=C(K^{-1})\int\omega \quad (12)$$

where

$C=diag\left[c_1,c_2,c_3\right]$ with $c_i>0,\ i=1,2,3$ is scalar.

D and K are positive constants.

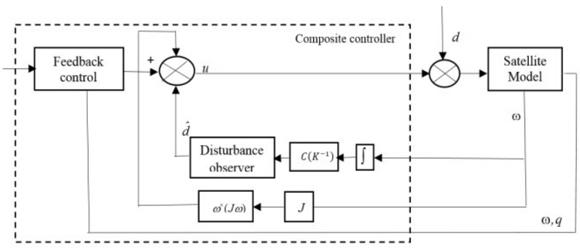


Fig. 1 Block diagram of the composite controller

In order to demonstrate the system stability, the following Lyapunov candidate function is considered :

$$\begin{aligned} V &= \frac{1}{2}\omega^{\mathrm{T}}K^{-1}J\omega+q^{T}q+(q_0-1)^2+\frac{1}{2}C^{-1}e^{\mathrm{T}}e \\ &= \frac{1}{2}\omega^{\mathrm{T}}K^{-1}J\omega+2(1-q_0)+\frac{1}{2}C^{-1}e^{\mathrm{T}}e \end{aligned} \quad (13)$$

where

$e=d-\hat{d}$ is the disturbance estimation error, thus $\dot{V}$ is given by

$$\begin{aligned} \dot{V} &= \omega^{\mathrm{T}}K^{-1}J\dot{\omega}-2\dot{q}_0+C^{-1}e^{\mathrm{T}}\dot{e} \\ &= \omega^{\mathrm{T}}K^{-1}[-\omega^{\times}(J\omega)+u+d]-2\dot{q}_0+C^{-1}e^{\mathrm{T}}\dot{e} \end{aligned} \quad (14)$$

Using the expresion of u in equation (11), the equation (14) becomes:

$$\dot{V}=-\omega^{\mathrm{T}}K^{-1}D\omega+\omega^{\mathrm{T}}K^{-1}e+C^{-1}e^{\mathrm{T}}\dot{e} \quad (15)$$

The derivative of the disturbnace observer can be computed as fellow

$$\dot{\hat{d}}=C(K^{-1})\omega \quad (16)$$

Substituting (16) into (15) gives

$$\dot{V}=-\omega^{\mathrm{T}}K^{-1}D\omega+\left(C^{-1}\dot{\hat{d}}\right)^{T}e+C^{-1}e^{\mathrm{T}}\dot{e} \quad (17)$$

Let $\dot{e}=\dot{d}-\dot{\hat{d}}$ according to the above assumption ($\dot{d}\approx 0$) then $\dot{e}\approx-\dot{\hat{d}}$.

Then (17) gives

$$\dot{V}=-\omega^{\mathrm{T}}K^{-1}D\omega-C^{-1}\left(\dot{e}\right)^{T}e+C^{-1}e^{\mathrm{T}}\dot{e} \quad (18)$$

Hence

$$\dot{V}=-\omega^{\mathrm{T}}K^{-1}D\omega \quad (20)$$

Is satisfied

$$\dot{V}\leq 0 \quad (21)$$

Since $\dot{V}$ is semi-negative definite then the asymptotic stability has been proved. Hence, the negativeness of $\dot{V}$ insures the system asymptotic stability.

3. RESULTS AND DISCUSSION

To assess the effectiveness of the planned control systems, numerical simulations were carried out under the Matlab/Simulink platform.The satellite parameters (used in the simulation) are illusterated in the following table.

Table1 Satellite simulation parameters.

Parameter	Value
Inertia[$kg.m^2$]	$\begin{bmatrix} 152.9 & 0 & 0 \\ 0 & 152.5 & 0 \\ 0 & 0 & 4.91 \end{bmatrix}$
Orbit [km]	686
Inclination [$\deg$]	98
Initial attitude [$\deg$]	[0 0 0]
Initial attitude rate [$\deg/s$]	[0 −0.06 0]
External Torques [$N.m$]	$\left(\lVert\omega\rVert^2+0.005\right)\begin{bmatrix} 0.05\sin(0.8t) \\ 0.05\cos(0.5t) \\ 0.05\cos(0.3t) \end{bmatrix}$

Gains tuning method allows choosing of controller gains as $: D = 95$, $K = 0.05$, $\boldsymbol{C} = diag(385, 296, 125)$

The control objective is to transfer the system from the initial attitude to the desired attitude, the simulation results are shown in figures 2-8.

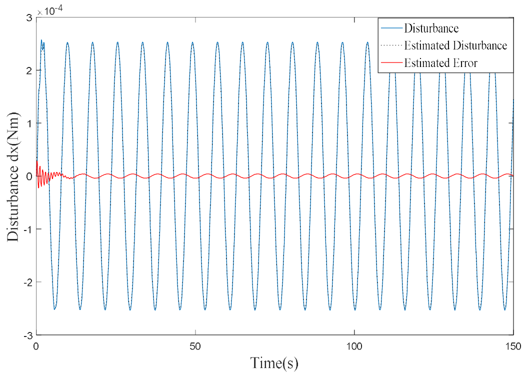


Fig. 2 Time responses of Disturbance dx

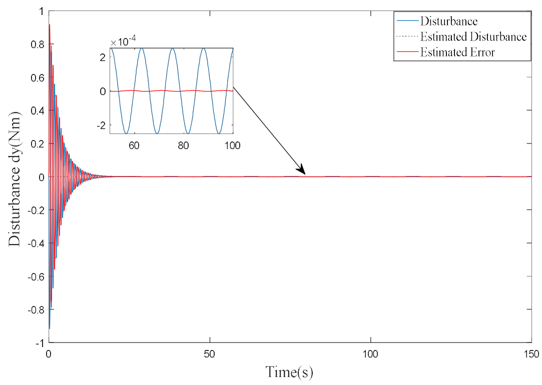


Fig. 2. Time responses of Disturbance dy

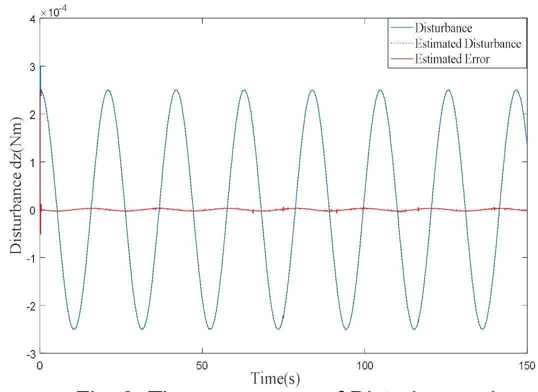


Fig. 3. Time responses of Disturbance dz

Figures 1-3 show the time evolutions of disturbances, disturbances estimations and estimation error according the three axes respectively, it is clear that the proposed controller can effectively estimate the uncertain disturbances. The control torques of three axes are given in Fig. 4. It is seen that at the beginning of the simulation, the control torque is important, the reason is that the proposed controller has better dynamic response than a classical control and can estimate compensate for the disturbances. Furthermore, after 7.2s, no excessive control energy is required to reject the disturbances.

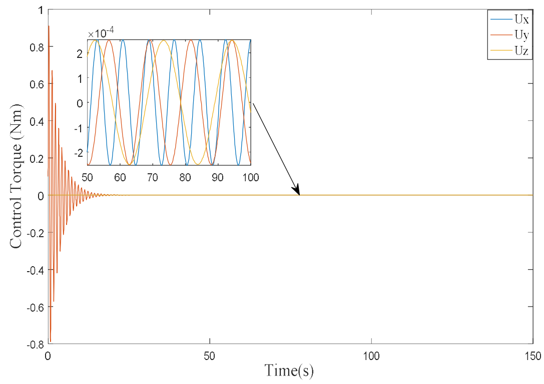


Fig. 4. Time response of control Torque

Fig. 5 and Fig. 6 illustrate the attitude control error and the quaternions error where the attitude control accuracy has been improved and the partial amplifications can demonstrate that the error has been perfectly reduced.

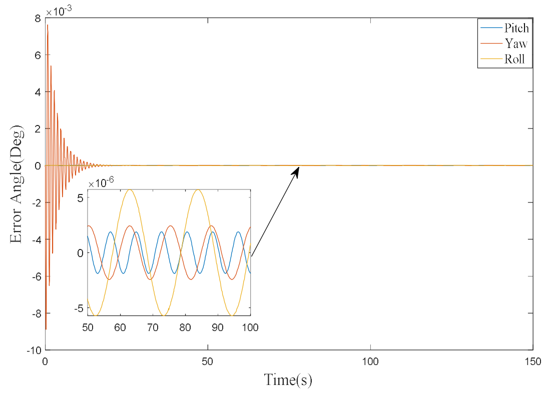


Fig.5.Attitude angle error

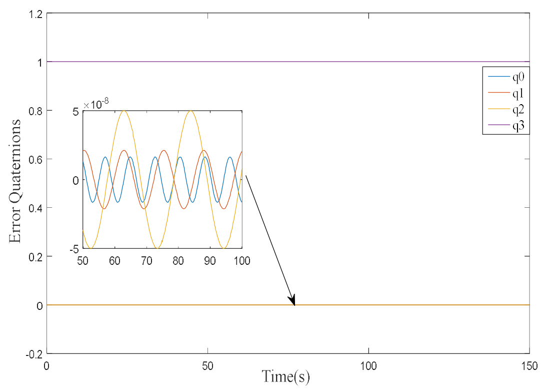


Fig. 6. Error quaternions

The responses of the spacecraft error angular velocity components are depicted in Fig 7. It can be seen that the stabilization is obviously improved using the proposed controller.

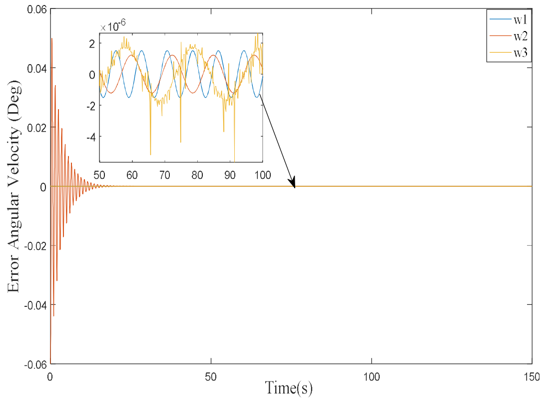


Fig. 8 Error angular velocity

For more detailed analysis, the root mean square (RMS) values of error results are computed for the time period 100-150 sec, which are presented in theTable2.

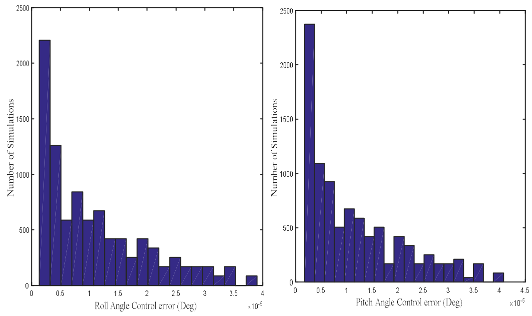
Table 2 RMS errors of the attitude

	RMS With Observer	**RMS Without Observer**
Roll (Deg)	0.168e-5	0.196e-3
Pitch (Deg)	0.551e-2	0.960e-1
Yaw (Deg)	0.506e-5	0.363e-3
	Magnitude of error	**Magnitude of error**
Attitude (Deg)	0.547e-2	0.960e-1

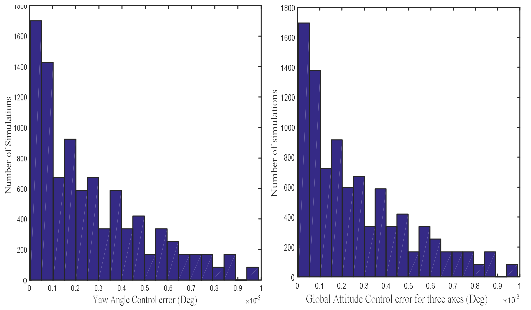
Table 2 presents the attitude errors which are improved when associating the observer with the controller; the roll and yaw angles errors where improved from the order 1.10^{-3} (deg), to the order1.10^{-5} (deg), the pitch angle error was also improved from the order 1.10^{-1} (deg), to the order 1.10^{-2} (deg), that can clearly confirms the usefulness of the observer.

Stochastic simulations

The static simulation consists of 10000 simulation runs, where the main objective is to analyse the way, in which the accuracy performance of the used method on a rigid satellite during attitude control has been carried out. for each Monte-Carlo run, the angle rates control errors along the three axes were picked randomly in the interval [-1 1] with the step of 0.1°/s. The global magnitude error is always kept below 1.10^{-3} (deg), for every simulation, the Monte Carlo test shows how the desired adaptive controller was made robust against disturbances.



(a) Roll error(b) Pitch error



(c) Yaw error(d) Global attitude error

Fig. 9Histogram of Euler angles control errors

4. CONCLUSIONS

Rigid spacecraft attitude control with uncertain disturbances has been addressed using a new adaptive PD method that combines adaptive method to PD controller. The proposed approach allows overcoming the disturbance variations effect on the controller and improving the pointing accuracy. The convergence error as well as the system stability are proved theoretically and verified using Lyapunov analysis.

The simulation results have been performed using MATLAB/SIMULINK environment. The simulation results show clearly the attitude angles convergence; hence, the controller can achieve perfectly the required pointing accuracy and spacecraft stabilization. Simulation results can also illustrate the proposed method feasibility, which provides a useful and promising way to treat attitude control of rigid spacecraft. Furthermore, the effectiveness of using the proposed method is analysed through Monte Carlo simulations test.

Some perspectives of this work can be also oriented toward the optimization of the controller gains, development of the proposed controller to deal with inertia uncertainties problem and taking into account the flexibility, the vibrations and the sloshing phenomena in order to construct a robust controller with better performances.

Acknowledgment

The authors: Benmansour Jalal Eddine and Benfriha Elhassen, dedicate this paper to the memory of the author Bellar Abdellatif.

References

[1] Z. Zhu, X. Yuanqing, F, Mengyin. Attitude stabilization of rigid spacecraft with finite-time convergence. International Journal of Robust and Nonlinear Control 2011; 21(6), 686-702.

[2] J. E. Benmansour, B. Khouane, andR. Rima,. High Precision Roll/Yaw Attitude Stabilization for Flexible communication satellite. *Algerian Journal of Signals and Systems*, (2018). *3*(2), 81-88..

[3] E. BENFRIHA, Bang-Bang Attitude Control During East-West Station Keeping For Geostationary Satellite. *Algerian Journal of Signals and Systems*, 2021. *6*(3), 163-168.

[4] ME. Cheriet, A. Bellar, MY. Ghaffour, A Adnane,MA Mohammed,. Inertia tensor estimation for a rigid nadir pointing satellite based on star tracker. Advances in aircraft and spacecraft science. 2021, 8(2), 111-126.

[5] J. Su, Z, Ruifeng, C, Kaiyuan. Globally Stabilizing PID Attitude Control of Rigid Body Based on MRP. Acta Aeronautica et Astronautica Sinica 2011, 32(4), 710-719.

[6] H. Schaub, JL. Junkins, RD, Robinett. New penalty functions and optimal control formulation for spacecraft attitude control problems. Journal of Guidance, Control, and Dynamics. 1997; 20(3), 428-434.

[7] Z. Wang, Y. LI. Rigid spacecraft robust optimal attitude stabilization under actuator misalignments. Aerospace Science and Technology, 2020, 105, 105990.

[8] R. Chai, et al. Review of advanced guidance and control algorithms for space/aerospace vehicles. Progress in Aerospace Sciences. 2021; 122, 100696.

[9] M. Kim, SH. JANG, H.Leeghim. Sliding Mode Attitude Control of Spacecraft Considering Angular Rate Constraints. Journal of the Korean Society for Aeronautical & Space Sciences, 2021 (49)2: 129-138

[10] E. Abdulhamitbilal, EM. Jafarov. Design of Sliding Mode Attitude Control for Communication Spacecraft. INTECH Open Access Publisher. 2012; 153-176.

[11] Z.Luwen,B. Chengchao, G. Jifeng, Z.Han,. Spacecraft attitude sliding mode control method design. *IEEE* Chinese Guidance, Navigation and Control Conference(CGNCC) IEEE. 2016; 2355-2360.

[12] AG. Parlos, JW. Sunkel. Adaptive attitude control and momentum management for large-angle spacecraft maneuvers. Journal of guidance, control, and dynamics, 1992; 15(4), 1018-1028.

[13] W. Luo, YC. Chu, KV. Ling. Inverse optimal adaptive control for attitude tracking of spacecraft. IEEE Transactions on Automatic Control, 2005; 50(11), 1639-1654.

[14] GS. Huang, HJ. Uang. Robust adaptive PID tracking control design for uncertain spacecraft systems: a fuzzy approach. IEEE Transactions on Aerospace and Electronic systems. 2006; 42(4), 1506-1514.

[15] Y. Yang. Attitude control in spacecraft orbit-raising using a reduced quaternion model. Advances in aircraft and spacecraft science. 2014; 1(4), 427.

[16] S. Ulrich, DL. Hayhurst, OA. Saenz Miller D, Barkana, I. Simple adaptive control for spacecraft proximity operations. In AIAA guidance, navigation, and control conference. 2014; (p. 1288).

[17] De Ruiter AH. Observer-based adaptive spacecraft attitude control with guaranteed performance bounds. IEEE Transactions on Automatic Control. 2015; 61(10), 3146-3151.

[18] B. Brahim A, Dhahri S, Ben Hmida F, Sellami, A. Adaptive sliding mode fault tolerant control design for uncertain nonlinear systems with multiplicative faults: Takagi–Sugeno fuzzy approach. Journal of Systems and Control Engineering. 2020; 234(2), 147-159.

[19] Wie, B. Space vehicle dynamics and control. Aiaa. 1998.

[20] K. Lu, Y. Xia Z. Zhu, Basin MV. Sliding mode attitude tracking of rigid spacecraft with disturbances. Journal of the Franklin Institute. 2012; 349(2), 413-440.

[21] Yang Y,Zhou Z. Attitude estimation: with or without spacecraft dynamics. Advances in aircraft and spacecraft science. 2017; 4(3), 335.

[22] F. Xie, A. Zhang, H. Zhang, Satellite attitude control based on backstepping adaptive sliding-mode method. *In 2018 Chinese Automation Congress (CAC)*. IEEE, 2018. 3329-3333.