UNIVERSITY POLITEHNICA OF BUCHAREST
FACULTY OF AEROSPACE ENGINEERING

PDH THESIS

GYRO SYSTEMS FOR SPACECRAFT ORIENTATION AND STABILIZATION

SUMMARY

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ABSTRACT

The thesis deals with the stabilization and control of sattelites' attitude using different clusters of control moment gyros (four pyramidal configurations) or inertial wheels (standard, tetrahedral and pyramidal configurations) as actuators; the dynamic inversion, neural networks, backstepping method are the main control methods used for the the stabilization and control of sattelites' attitude. The first chapter defines the attitude of the satellites which expresses the position of the satellite tied frame with respect to the local orbital frame, through the Euler angles and quaternion vectors. It is also addressed the problem of the automatic control of the satellites' attitude using feedbacks after the vector $\boldsymbol{q}$, the angular speed vector ($\boldsymbol{\omega}$), with saturation zones after the two vectors ($\boldsymbol{q}$ and $\boldsymbol{\omega}$). The control law is PD type and has a component depending on the moment generated by the inertial wheels; the system follows the model of the reference frame. In the second chapter, one presented a study regarding the actuators with inertial wheels (different configurations) used in the stabilization systems f the satellites' attitude. Then, it is designed a new automatic configuration of the satellite's attitude using the backstepping method with different actuators (inertial wheel type). In the third chapter, one elaborates patterns for the four pyramidal clusters with CMGs/VSCMGs; there is also designed a new automatic architecture for the control of satellite's attitude using a control law having a PI component after the quaternion vector $\boldsymbol{q}$ and a proportional component after the angular velocity of the satellite; as actuator, the automatic control system uses a pyramidal structure with CMGs. In the fourth chapter, there are presented different automatic attitude control structures by using four different pyramidal clusters with VSCMGs. Such control systems are designed by means of PD laws and similar systems to further control of the stored power by the pyramidal clusters and to equalize the angular velocity of the gyroscopic rotors, respectively. The fifth chapter presents a study on the singularities of the systems having CMGs/VSCMGs; one defines the envelope of the total kinetic moment for the VSCMGs' clusters. In this final chapter, the general conclusions, the personal contributions and further research developments are presented.

KEYWORDS:

Control moment gyro
Inertial wheel
Pyramidal cluster
Control of attitude
Satellite
Singularity
Neural networks

SHORT PRESENTATION OF THE THESIS

Chapter 1

This chapter presents the necessity, timeliness and importance of the topic addressed. The specific objectives of the research are also presented.

A key issue in satellites' missions is the calculation and the control of the satellites. Therefore, it was also the subject of much scientific research works. Among these, there may be mentioned the works [1], [8], [10], [21], [68], [69], [73], [78], [79], [80], [82].

The first chapter defines the attitude of the satellite (S) which expresses the position of the satellite tied frame with respect to the local orbital frame, through the Euler angles and quaternion vectors; relative rotation and the transport matrices are also defined. The quaternion vectors are calculated as the kinematic solutions of differential equations, depending on the relative, transport and absolute angular velocities. By identifying of the attitude matrices expressed by Euler angles or by the quaternion vectors, one established calculation relationships for the Euler angles with respect to the quaternion vectors; also, one sets calculation relations for the roll, pitch and yaw angular speeds with respect to the angular speeds around the axes of the satellite tied reference system.

It is also addressed the problem of the automatic control of the satellites' attitude using feedbacks after the vector $\boldsymbol{q}$, the angular speed vector ($\boldsymbol{\omega}$), with saturation zones after the two vectors ($\boldsymbol{q}$ and $\boldsymbol{\omega}$). The motion control law is designed such that the satellite S performs a typical maneuver around its own axis, consisting of three phases [78]: 1) accelerated angular movement; 2) free (uniform) motion; 3) decelerated motion. For the automatic control architecture, the Matlab/Simulink model is built and the time characteristics expressing the dynamics of the state and command variables. Also, one studied the problem of the automatic control of the satellite's attitude and stored energy using inertial wheels such that S follows two targets: the sun and the earth station. The automatic control system first makes the initialization using the thrusters; in this stage, moves fat, with ample rotations such that the axis of the solar panels is oriented toward the sun, and the satellite's symmetry axis is oriented toward a ground station. In the second stage, the control system permanentely follows the two targets in the same time with the control of the stored energy, using inertial wheels; the inertial wheels are accelerated during exposure to the sun by absorbing the energy supplied by the solar panels, creating, as feedback, command moments for the satellite's motion; during the eclipse, the inertial wheels are deccelerate by consuming the stored energy during their acceleration stage. The control law is PD type and has a component depending on the moment generated by the inertial wheels [69]; the system follows the model of the reference frame [40]. For the automatic control system of the satellite's attitude, one obtained the Matlab/ Simulink model and its dynamic characteristics.

Chapter 2

In the second chapter, one presented a study regarding the actuators with inertial wheels (different configurations) used in the stabilization systems f the satellites' attitude; the study is based on the following works [15], [19], [22], [23], [28], [30], [31], [32], [34], [55], [58], [63], [64], [66], [67]. First of all, the standard configuration is presented; it has three inertial wheels (configuration having the rotors' axes parallel to the axes satellite tied frame) and then pyramidal and tetrahedron configurations. One deduced the dynamic models of the ensemble satellite-actuator for all these configurations. Then, it is designed a new automatic configuration of the satellite's attitude using the backstepping method with different actuators (inertial wheel type). The system has two subsystems: 1) the attitude controller which provides the vector of generator couple; 2) the calculation block of the imposed angular velocities of the inertial wheels relative to the satellite; 3) the controller for the vector of inertial wheels' angular velocities; 4) the controller for the vector of inertial wheelss couple; 5) the modeling block of the actuator with inertial wheels; 6) the modeling block of the satellite's dynamics. Matlab/Simulink models are obtained for the control systems with actuators in standard, pyramidal and tetrahedron configurations. Using these and the afferent software, one obtained the dynamic characteristics of the system. In the event of a wheel's failure, one changes the matrix expressing the dependence between the moments generated by the inertial wheels and the moments induced after the axes of the satellite tied frame; dynamic characteristics of the system are plotted with actuators and tetrahedral pyramidal configuration in case of failure of a wheel of inertia; in this case, the other three take charge of the damaged wheel.

Chapter 3

In the third chapter, one elaborates patterns for the four pyramidal clusters with CMGs/ VSCMGs, structures that are presented and studied in the papers [8], [54], [75], [81]. The inertial wheels (RI) are manoeuvrable and produce small rotations of S; they have the disadvantage that, for carrying out extensive maneuvers, large wheels are required; the created couples depend on the wheel's dimensions. Thus, to create large control couples, RI should be large and therefore heavy loads. Therefore, the inertia wheels are used to the stabilization of the small satellites' attitude; the inertial wheels produce torques of maximum 1.5 Nm. The CMGs provide important control couples (up to 3000 Nm), with kinetic momentum up to 3000 Nms. An embodiment of the CMG is VSCMG (CMG with variable proper angular velocity). Having a degree of freedom in addition, VSCMGs have the possibility of storing energy while controlling attitude. For each of the four versions of pyramidal structures, there are calculated the gyro moments generated by each CMG/VSCMG by the axes of S and the resultant moments generated by the pyramidal architectures after the same axes of the satellite. Also, the matrix expressing the dependence between the resultant gyro moment vector and the vector of the gyro frames' agular velocities as well as the cosines' matrices of the angles between the axes of the satellite tied pyramidal frame, respectively, the axes of rotation of the gyros, the transversal axes of the CMGs/VSCMGs and the axes of rotation of the rotary frame; these matrices are useful for the calculation of the inertia moments of the satellite. In the second part of the chapter, there is designed a new automatic architecture for the control of satellite's attitude using a control law having a PI component after the quaternion vector $\boldsymbol{q}$ and a proportional component after the angular velocity of the satellite. As actuator, the automatic control system uses a pyramidal structure with CMGs. The Matlab/Simulink model is built and the afferent software; with these, the dynamic characteristics of the system are plotted for the pyramidal with CMGs.

Chapter 4

In the fourth chapter, there are presented different automatic attitude control structures by using four different pyramidal clusters with VSCMGs. Such control systems are designed by means of PD laws and similar systems to further control of the stored power by the pyramidal clusters and to equalize the angular velocity of the gyroscopic rotors, respectively. One built Matlab/Simulink models and, with these, the characteristics for the systems are obtained (for all four variants of pyramidal clusters with VSCMGs). Then, there are designed adaptive attitude control structures using one of the four different clusters with VSCMGs; these systems use the estimates of the inertia moment matrices and of the dynamic damping matrices; similar systems are designed for the additional control of the power stored by the pyramidal clusters, respectively, for the equalization of the gyro rotors' angular velocities. For all these systems, Matlab/Simulink models are obtained and, using these, time characteristics resulted. Also, there are designed adaptive attitude control structures using one of the variants cluster VSCMGs; the dynamic inversion method is used together with neural networks; there are designed architectures with additional control power stored by the pyramidal clusters, respectively, for the equalization of the gyro rotors' angular velocities. Matlab/Simulink models are obtained and time characteristics resulted.

Chapter 5

The fifth chapter presents a study on the singularities of the systems having CMGs/ VSCMGs, this being a problem studied recently by many researchers [18], [20], [29], [36], [37], [53] [56], [57], [60], [61], [71], [76], [81], [82]. There is disclosed a system model of a CMGs/VSCMGs, with an emphasis on the single state. It discloses a method for avoiding singularities using zero motion without power control method based on the calculation of the gradient of the singularity conditioning factor as a measure of their neighborhood. One defines the envelope of the total kinetic moment for the VSCMGs' clusters.

Chapter 6

In this final chapter, the general conclusions, the personal contributions and further research developments are presented.

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REFERENCES

[1] Ahmed, J., Coppola, V., Bernstein, D.S. *Adaptive Asymptotic Tracking of Spacecraft Attitude Motion with Inertia Matrix Identification.* Journal of Guidance, Control and Dynamics, vol. 21, no. 5, 1998, pp. 684-691.

[2] Aron, I., Lungu, R. *Automate de stabilizare şi dirijare*. Military Publisher, Bucharest, 1991.

[3] Aron, I., Lungu, R. *Automatica girostabilizatoarelor*. Enciclopedica Publisher, Bucharest, 1994.

[4] Aron, I., Lungu, R. Cismaru, C. *Sisteme de navigaţie aerospaţială*. Scrisul Românesc Publisher, Craiova, 1989.

[5] Bang, H., Ha, C., Kim, J.H. *Flexible Spacecraft Attitude Maneuver by application of Sliding Mode Control*. Acta Astronautica, vol. 57, 2005, pp. 841-850.

[6] Behal, A., Dawson, D., Zergheroglu, E., Fang, Y. *Nonlinear Tracking Control of an Underactuated Spacecraft*. Journal of Guidance, Control and Dynamics, vol. 25, no. 5, 2002, pp. 979-985.

[7] Belea, C. *Automatică neliniară*. Editura Tehnică, Bucureşti, 1983.

[8] Berner, R. *Control Moment Gyro Actuator for Small Satellite Applications*. Thesis of Master of Science. University of Stellenbosch, South Africa, 2005.

[9] Bedrossian, N.S., Paradiso, J., Bergmann, E.V., and Rowell, D. *Redundant single gimbal control moment gyroscope singularity analysis*. Journal of Guidance, Control, and Dynamics, vol. 13, nr. 6, 1998, pp. 1096-1101.

[10] Bilimoria, K., Wie, B. *Time-Optimal Three-Axis Reorientation of a Rigid Spacecraft*. Journal of Guidance, Control and Dynamics, vol. 16, no. 3, 1993, pp. 446-452.

[11] Calise, A.J., Hovakymyan, N., Idan, M. *Adaptive Output Control of Nonlinear Systems Using Neural Networks.* Automatica, vol. 37, no. 8, 2001, pp. 1201-1211.

[12] Calise, A.J., Johnson, E.N., Johnson, M.D., Corban, J.E. *Applications of Adaptive Neural – Networks Control to Unmanned Aerial Vehicles.* Journal of Harbin Institute of Technology, 2006, vol. 38, no. 11, pp. 1865-1869.

[13] Calise, A.J., Lee, H., Kim, N. *High Bandwith Adaptive Flight Control.* AIAA Guidance, Navigation and Control Conference. 14-17 August, 2000.

[14] Calise, A.J., Lee, S., Sharma, M. *Direct Adaptive Reconfigurable Control of a Tailless Fighter Aircraft.* In Rev. American Institute of Aeronautics and Astronautics, Georgia, USA.

[15] Chen, X., Sun, H., Zhang, J. *Reaction Wheels Momentum Dumping by Hybrid Control of Magnetorquers and Thrusters*. AIAA Guidance, Navigation and Control Conference, 2010.

[16] Chwa, D., Choi, J. *Adaptive Nonlinear Guidance Law Considering Control Loop Dynamics*. IEEE Transactions on Aerospace and Electronic Systems, vol. 39, no. 4, October, 2003, pp. 1134-1143.

[17] Circi, C. *Three-axis Attitude Control using Combinated Gravity-Gradient and Solar Pressure*. Journal of Aerospace Engineering, 2007.

[18] Cornick, D.E. *Singularity avoidance control laws for single gimbal control moment gyros*. Proceedings of the AIAA Guidance and Control Conference, New York, 1979, pp. 20-33.

[19] Doruk, R.O. *Nonlinear Controller Design for a Reaction Wheel Actuated Observatory Stallite.* PhD. Thesis. Middle East Technical University, 2008.

[20] Ford, K., Hall, C. *Singular Direction Avoidance Steering for Control Moment Gyro*. Journal of Guidance, Control and Dynamics, vol. 23, no. 4, 2000, pp. 648-656.

[21] Hahlani, H. *Design of a Payload Control System for Tracking Moving Objects.* Journal of Guidance, Control and Dynamics, vol. 12, no. 3, 1989, pp. 365-374.

[22] Halelani, H.B. *Sun-Tracking Commands and Reaction Wheel Sizing with Configuration Optimization*. Journal of Guidance, Control, and Dynamics, vol. 17, no. 4, 1994.

[23] Hall, C.D., Tsiostras, P., Shen, H. *Tracking Rigid Body Motion using Thrusters and Momentum*

Wheels. Journal of Astronautical Sciences, vol. 50, no. 3, 2003, pp. 311-323.

[24] Hovakimyan, N., Nardi, F., Calise, A.J. *A Novel Error Observer Based Adaptive Output Feedback Approach for Control of Uncertain Systems.* IEEE Tran. on Automatic Control, vol. 47, 2002.

[25] **Ioan, M.**, Lungu, M., Lungu, R. *Control of the Satellites' Attitude using a Pyramidal Configuration of Four Variable Speed Control Moment Gyros*. Scientific Bulletin – University Politehnica Bucharest, Series D: Mechanical Engineering, ISSN: 1454-2358, 2017. In process of publishing.

[26] Isidori, A. *Nonlinear Control Systems.* Springher Publisher, Berlin, 1995.

[27] Ives, N.E. *The Effect od Solar Radiation Pressure on the Attitude Control of an Artificial Satellite*. Aeronautical Research Council Reports and Memorando, 1963.

[28] Johanssen, S. *ESMO ADCS Redudancy Management*. Master Thesis. Narvik University College, 2006.

[29] Junkins, J., Kim, Y. *Introduction to Dynamics and Control of Flexible Structures*, New York, 1993, pp. 48-49.

[30] Karatas, S. *LEO Satelites: Dynamic, Modeling, Simulations and Some Nonlinear Attitude Control Techniques*. Master Thesis. Middle East Technical University, 2006.

[31] Kim, K., Kim, Y. *Robust Backstepping Control for Slew Maneuver using Nonlinear Tracking Function*. Journal of Control Systems Technology. IEEE Transactions on Control Systems Technology, vol. 11, no. 6, 2003, pp. 822-829.

[32] Kim, B., Lee, H. *Three-axis Reaction Wheel Attitude Control System for KITSAT-3 Microsatellite*, 2008.

[33] Kok, I. *Comparison and Analysis of Attitude Control Systems of a Satellite using Reaction wheel Actuators.* Master Thesis. University of Wurzburg, 2012.

[34] Kristiansen, R. *Attitude Control of Microsatelite*. Master Thesis. Department of Engineering Cybermetrics, NTNU, 2000.

[35] Kristiansen, R., Nicklasson, P.J. *Satellite Attitude Control by Quaternion-Based Backstepping*. American Control Conference, June 8-10, Portland, USA, 2005.

[36] Kurokawa, H. *Constrained steering law of pyramid-type control moment gyros and ground tests*. Journal of Guidance, Control, and Dynamics, vol. 20, no. 3, 1997, pp. 445-449.

[37] Kurokawa, H. *A geometry study of single gimbal control moment gyros - singularity problem and steering law*. Tech. Rep. Report No.175, Mechanical Engineering Laboratory, Japan, January 1998.

[38] Kurokawa, H., Yajima, N. *A study of CMG systems - for selection and evaluation*. Proceedings of 16th International Symposium on Space Technology and Science, (Japan), 1988, pp. 1243-1249.

[39] Li, C., Ma, G., Song, B. *Spacecraft Attitude Determination and Control on Nonlinear H_∞ Control*. 1st International Symposium on Systems and Control in Aeronautics and Astronautics ISSCAA, 2006, pp. 395-399.

[40] Lungu, M. *Sisteme de conducere a zborului.* Sitech Publisher, Craiova, 2008.

[41] Lungu, M. *Algoritmi si structuri pentru identificarea, estimarea si conducerea zborului aeronavelor si rachetelor*. Sitech Publisher, Craiova, 2013.

[42] Lungu, M., Lungu R. *Estimarea stării aparatelor de zbor*. Sitech Publisher, Craiova, 2014.

[43] Lungu, M., Lungu, R. *Estimarea stării aparatelor de zbor – Lucrari practice de laborator*, Sitech Publisher, Craiova, 2014.

[44] Lungu, R. *Echipamente şi sisteme giroscopice*. Universitaria Publisher, Craiova, 1997.

[45] Lungu, R. *Sisteme de dirijare aerospaţială.* Sitech Publisher, Craiova, 2002.

[46] Lungu, R. *Automatizarea aparatelor de zbor.* Universitaria Publisher, Craiova, 2000.

[47] Lungu, R., Lungu M. *Controlul automat al aeronavelor la aterizare*. Sitech Publisher, Craiova, 2015.

[48] Lungu, R., Lungu, M., **Ioan, M**. *Nonlinear Automatic Control of the Satellites by using the Quaternion and the Angular Velocities' Vectors*. 3rd International Workshop on Numerical Modeling in Aerospace Sciences (NMAS 2015), Bucureşti, 2015.

[49] Lungu, R., Lungu, M., **Ioan, M**. *Determination and Control of the Satellites' Attitude by using a Pyramidal Configuration of Four Control Moment Gyros*. 12th International Conference on Informatics in Control, Automation and Robotics, Colmar, France, 21-23 July 2015, pp. 448-456.

[50] Lungu, M., Lungu, R., **Ioan, M**. *Automatic Control of the Satellites' Attitude and Stored Energy using Inertial Wheels*. 17th International Carpathian Control Conference (ICCC 2016), Tatranská Lomnica, Slovak Republic, May 29 - June 1, 2016, pp. 455-460.

[51] Luo, W., Chy, Y.C., Ling, K.V. *Inverse Optimal Adaptive Control for Attitude Tracking of Spacecraft*. Journal of Automatic Control, IEEE Transactions, vol. 50, pp. 1639-1654, 2005.

[52] Mackunis, W., Dupre, K., Fitz-Coy, N., Dixon, W.E. *Adaptive Satellite Control in the Presence of Inertia and CMG Gimbal Friction Uncertainties.* Journal of Astronautical Science, vol. 56, no. 1, 2008, pp. 121-134.

[53] Margulies, G., Aubrun, J.N. *Geometric theory of single-gimbal control moment gyro systems*. Journal of the Astronautical Science, vol. 26, no. 2, 1978, pp. 159-191.

[54] McChesney, C. *Design of Attitude Control Actuators for a Simulated Spacecraft*. Thesis of Master of Science, Department of Air Force University, Ohio, 2011.

[55] Obispo, S.L. *Control and Sensor Development on a Four Wheel Pyramidal Reaction Wheel Platform*. Master Thesis. California Polytechnic University, 2008.

[56] Oh, H., Vadali, S. *Feedback control and steering laws for spacecraft using single gimbal control moment gyro*. The Journal of the Astronautical Sciences, vol. 39, no. 2, 1991, pp. 183-203.

[57] Paradiso, J.A. *Global steering of single gimballed control moment gyroscopes using a directed search*. Journal of Guidance, Control, and Dynamics, vol. 15, 1992, pp. 1236-1244.

[58] Pedersen, M. *Nonlinear Attitude Control of the Microsatellite ESEO*. Master Thesis. Norvegian University Science and Technology, 2003.

[59] Pinheiro, E.R., Gadelca de Souza, L.C. *Design of the Microsatellite Attitude Control System using the Mixed* H_2 / H_∞ *Method via LMI Optimization*. Mathematical Problems in Engineering, 2013.

[60] Schaub, H., Junkins, J.L. *Singularity avoidance using null motion and variable-speed control moment gyros*. Journal of Guidance Control, and Dynamics, vol. 23, no. 1, 2000, pp. 11-16.

[61] Schaub, H., Vadali, S.R., Junkins, J.L. *Feedback control law for variable speed control moment gyroscopes*. Journal of the Astronautical Sciences, vol. 46, no. 3, 1998, pp. 307-328.

[62] Sharma, M., Calise, A., *Adaptive Trajectory Control for Autonomous Helicopters.* AIAA Guidance, Navigation and Control Conference, 14-17 August, 2001, Montreal, Canada.

[63] Shirazi, A., Mirsharus, M. *Pyramidal Reaction Wheel Arrangement Optimization od Satellite Attitude Control Subsystem for Minimizing Power Consumption*. Journal of Aeronautical and Space. Sci 15 (2), pp.190-198, 2014.

[64] Sidi, M. *Spacecraft Dynamics and Control*. Cambridge University Press, 1997.

[65] Skelton, C.E., Hall, C.D. *Mixed Control Moment Gyro and Moemntum Wheel Attitude Control Strategies*. American Astronautics Society, 2003.

[66] Ştefănescu, M.R. *Sisteme de reglare automată a atitudinii sateliţilor*. PhD Thesis, University Politechnica of Bucharest, 2016.

[67] Tregouet, J.F., Arzelier, D., Peaucelle, D., Pittet, C. *Reaction Wheels Desaturation using Magnetorquers and Static Input allocation*. Journal Control Systems Technology, 2013.

[68] Tsiostras, P. *Stabilization and Optimality Results for the Attitude Control Problem*. Journal of Guidance, Control and Dynamics, vol. 19, no. 4, 1996, pp. 772-779.

[69] Tsiostras, P., Shen, H., Hall, C. *Satellite Attitude Control and Power Tracking with Energy/ Momentml Wheels.* Journal of Guidance, Control and Dynamics, vol. 24, no. 1, 2001, pp. 23-34.

[70] Tsiotras, P., Shen, H., Hall, C. *Satellite Attitude Control and Power Tracking with Momentum Wheels.* AIAA Journal of Guidance, Control and Dynamics, vol. 24, no. 1, 2001, pp. 23-34.

[71] Vadali, S., Oh, H., Walker, S. *Preferred gimbal angles for single gimbal control moment gyros*. Journal of Guidance Control, and Dynamics, vol. 13, no. 6, 1990, pp. 1090-1095.

[72] Wang, Q., Yang, J. *The Application of error Quaternion and PID Control Method in Earth Observation Satellite's Attitude Control System*. Systems and Control in Aerospace and Aeronautics, 2006, pp. 128-131.

[73] Wen, J.T., Delgado, K. *The Attitude Control Problem*. IEEE Transactions on Automatic Control, vol. 36, no. 10, 1991, pp. 1372-1379.

[74] Wie, B. *Singularity analysis and visualization for single-gimbal control moment gyro systems.* AIAA Guidance, Navigation, and Control Conference, Austin, TX, August 2003.

[75] Wie, B., Bailey, D., Heiberg, C. *Rapid Multi-Target Acquisition and Pointing Control of Agile* Spacecraft. AIAA Guidance, Navigation and Control Conference, Denver, 2000.

[76] Wie, B., Bailey, D., Heiberg, C. *Singularity robust steering logic for redundant single-gimbal control moment gyros*. Journal of Guidance, Control, and Dynamics, vol. 24, no. 5, 2001, pp. 865-872.

[77] Wie, B., Bailey, D., Heiberg, C. *Acquisition and Pointing Control of Agile Spacecraft*. Journal of Guidance, Control and Dynamics, vol. 25, no. 1, 2002, pp. 96-104.

[78] Wie, B., Lu, J. *Feedback Control Logic for Spacecraft Eigenaxis Rotations Under Slew Rate and Control Constraints*. Journal of Guidance, Control and Dynamics, vol. 18, no. 6, 1995, pp. 1372-1379.

[79] Wie, B., Weiss, H., Arapostathis, A. *Quaternion Feedback Regulator for Spacecraft Eigenaxis Rotations*. Journal of Guidance, Control and Dynamics, vol. 18, no. 6, 1989, pp. 375-380.

[80] Wie, B., Bailey, D., Heiberg, C. *Rapid Multi-Target and Pointing Control of Agile Spacecraft*. AIAA Guidance, Navigation and Control Conference, Denver, CO, August 14-17, 2000. Journal of Guidance, Control, and Dynamics, vol. 25, no. 1, 2002, pp. 96-104.

[81] Yoon, H. *Spacecraft Attitude and Power Control using Variable Control Moment Gyros*. Thesis of Doctor of Philosophy, Georgia Institute of Technology, 2004.

[82] Yoon, H., Tsiotras, P. *Spacecraft Adaptive Attitude and Power Tracking with Variable Speed Control Moment Gyroscopes*. Journal of Guidance, Control and Dynamics, vol. 25, no. 6, 2002, pp. 1081-1090.

PUBLICATIONS OF THE AUTHOR DURING THE PHD STAGE

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2. Lungu, R., Lungu, M., **Ioan, M.** *Nonlinear Automatic Control of the Satellites by using the Quaternion and the Angular Velocities' Vectors*. 3rd International Workshop on Numerical Modeling in Aerospace Sciences (NMAS 2015), Bucureşti, 2015. INCAS Bulletin, Volume 7, Issue 2, 2015, pp. 93-103 ISSN 2066-8201. *Database: Copernicus*.

3. Lungu, R., Lungu, M., **Ioan, M.** *Determination and Control of the Satellites' Attitude by using a Pyramidal Configuration of Four Control Moment Gyros*. 12th International Conference on Informatics in Control, Automation and Robotics, Colmar, France, 21-23 July 2015, pp. 448-456. *Database: ISI Web of Science, IEEE Xplore*.

4. Lungu, M., Lungu, R., **Ioan, M.** *Automatic Control of the Satellites' Attitude and Stored Energy using Inertial Wheels*. 17th International Carpathian Control Conference (ICCC 2016), Tatranská Lomnica, Slovak Republic, May 29 - June 1, 2016, pp. 455-460. *Database: ISI Web of Science, IEEE Xplore*.