UNIVERSITY POLITEHNICA OF BUCHAREST
DOCTORAL SCHOOL OF AEROSPACE ENGINEERING

PDH THESIS

AUTOMATIC CONTROL OF SPACECRAFT ATTITUDE AND TRAJECTORY

SUMMARY

Thesis tutor:
Prof. PhD. Eng. Romulus LUNGU

Author:
Eng. Florentin-Alin BUŢU

Bucharest
2021

TABLE OF CONTENTS

ABSTRACT

The thesis deals with the automatic control of spacecraft, and, following stages of a space mission (launch, orbital maneuvers) proposes and presents the design of experimental control laws that are then implemented and tested in the Matlab/Simulink simulation environment. The first chapter addresses issues related to the dynamics of the carrier rocket and the automatic control of the attitude and trajectory of the flight for the first stage of the flight. An adaptive attitude control system is designed consisting of a reference model, a linear dynamic compensator, a state estimator and a neural network that has a role in compensating the approximation error of the function used in the dynamic inversion. In the second chapter, using the nonlinear dynamics rocket flight model, the structure of an automatic control system with the Backstepping method is designed to control the flight slope of a carrier rocket in the longitudinal plane, with reactions according to slope angle, pitch angle and pitch angular velocity. Also in the second chapter, an adaptive Sliding Mode control system is designed for a carrier rocket using the method of dynamic inversion of the nonlinear function that describes the dynamics of the slope angle. Chapter three presents a study of controlling the trajectory of a spacecraft in an orbit around Earth and a transfer orbit around the Moon modeled by the Patched Conic Approximation method. A law for controlling the motion of a spacecraft on the trajectory is designed, according to a non-linear control law based on the use of a positively defined Lyapunov function; it is expressed in terms of the vectors which represent the deviations of the position and velocity relative to those corresponding to the reference trajectory. Chapter four addresses issues of dynamics and control of the relative position and relative attitude of spacecraft in rendezvous missions. A law of non-linear adaptive control of the relative position and relative attitude of the chaser vehicle relative to the target vehicle is designed. Then, decoupling the dynamics model of the relative position from that of the relative attitude, two laws of nonlinear adaptive control are designed. The end of Chapter Four addresses the issue of optimal control of the position of the chaser vehicle relative to the target vehicle using the $H\infty$ method. Chapter five presents the realization of a Hardware / Software platform aimed at controlling the trajectory of the simulated model of a carrier rocket through a numerical controller that implements adaptive control law based on the concept of dynamic inversion and neural networks designed in the first chapter.

KEYWORDS:

Launch vehicle
Spacecraft
Trajectory control
Attitude control
Adaptive control
Dynamic inversion
Backstepping method
Sliding Mode control

SHORT PRESENTATION OF THE THESIS

Introduction

Flight into outer space is one of the most important technological achievements of mankind. It facilitated, in addition to exploring the cosmos, launching communications satellites or space telescopes, observing from another perspective the phenomena happening on planet Earth and significant development in directions such as weather forecasting, monitoring natural disasters (floods, fires, tsunamis, earthquakes, etc.), monitoring land use (forestry, agriculture) or mapping. There are, therefore, the premises for the continued presence of humans in outer space, as well as the development of viable technologies, which would allow this at the lowest possible cost and at the same time in conditions of maximum safety.

This paper addresses issues related to the automatic control of spacecraft, and, following phases of a space mission (launch, orbit insertion, orbital maneuvers) proposes and presents the design of experimental control laws that are then implemented and tested in the Matlab/Simulink simulation environment.

Chapter 1

The first chapter addresses issues related to the dynamics of the launch vehicle (carrier rocket) and the automatic control of the attitude and flight path for the first phase of the flight, until the detachment of the first stage. The forces and moments acting on the rocket (aerodynamic, weight and control) are highlighted first and the dynamics of the rocket (considering the rigid solid) is modeled using an inertial reference frame, the frame related to the rocket body, Euler's angles and the quaternion unit vector. The rocket control is performed by means of a rolling moment created by two reactive motors arranged near the tip of the missile and by a reaction nozzle mounted in gimbal suspension at the base of the missile; thus, the reaction force creates moments of rotation around the center or mass, in pitch and in yaw.

For the control of the rocket attitude, expressed by the quaternion vector $\mathbf{q}$, the concept of dynamic inversion is used [18], [53], [67]; the designed control law contains mainly two components: one of PD (proportional-derivative) type and one adaptive. The attitude adaptive control system consists of a reference model (control filter), a linear dynamic compensator, a state observer (estimator) and a neural network $\mathrm{NN_c}$ that has a role in compensating the $\boldsymbol{h}_\mathrm{r}$ function approximation error, used in dynamic inversion. The parameters of the model used in dynamic inversion are constantly updated by an online identification algorithm that uses the least squares method. For this control law, the corresponding model is implemented in the Matlab/Simulink simulation environment and the dynamic characteristics of the system are graphically represented. For the launch vehicle dynamic model, the data available for the Ares I launcher [8], [16], [28], [30], [33] is used.

Chapter 2

The second chapter presents issues regarding the multi-stage launch vehicle; a dynamic model of it is deduced considered as a material point and calculation relations for the sizing of single-stage and multi-stage rockets are deduced. The sizing of the rocket consists in calculating the minimum mass of fuel for each stage (fuel for which the value of the specific impulse is known), so that the rocket is able to carry a payload m_S to reach a required speed (after the consumption of the entire amount of fuel). Next, it is required to reach a desired altitude in a finite imposed time interval, when the vertical component of the speed is zero, and the horizontal one - maximum; the trajectory of the guided carrier rocket is calculated using an optimization criterion and choosing a performance indicator J. The optimization problem, Bolza type [22], [88] is solved and the optimal command is calculated, and at the end an optimal control law is obtained which is implemented using the Matlab/Simulink simulation environment. Following the numerical simulation, the dynamic characteristics obtained are graphically represented.

The structure of an automatic control system with the Backstepping method [42], [54], [83], [109] is then designed, using the nonlinear dynamic model of the rocket, to control the flight slope of a carrier rocket in the longitudinal plane, with reactions after the slope angle, the pitch angle and the pitch angular velocity. Also in the second chapter, an adaptive sliding mode control system is designed for a carrier rocket using the method of dynamic inversion of the nonlinear function that describes the dynamics of the slope angle. The control law obtained is described depending on the estimated variables, solutions of differential equations obtained from the condition of asymptotic stability of the closed-circuit system, using the method of Liapunov functions [18], [42], [43].

Chapter 3

Chapter three presents' issues regarding space flight dynamics and orbital transfer [14], [26], [49], [64], [71], [75], [77], [85]. A study on orbital motions is presented, highlighting the parameters of the motion of a spacecraft and the math relations for different categories of orbits: circular, elliptical, parabolic, hyperbolic. Then there are presented the relations of the parameters that describe the change of the shape and inclination of the orbits and, respectively, the transfer between coplanar orbits by impulsive maneuvers. Also, a study on the transfer between coplanar orbits is presented, by determining the orbit that ensures a minimum fuel consumption, a problem also studied in [75]. The transfer of a spacecraft from an orbit around a planet (for instance Earth) to an orbit around another celestial body (for instance Moon) can be done on an orbit shaped by different methods, among which we mention: Hohman transfer method [64], PCA method (patched conic approximation) [14], ballistic capture method [14], [26].

Then a study is presented on the control (stabilization) of the trajectory of a spacecraft on an orbit around the Earth and on a transfer orbit around the Moon modeled by the PCA (patched conic approximation) method, approximating the transfer path through two orbital arcs. The equations of motion in gravitational field of the spacecraft S (described as the material point of mass m) are expressed relative to the Sun (mass m_S), also taking into account the attractive forces of the Earth and the Moon with the respective masses m_P and m_L. The command is considered F_T - the resulting traction force of the engines with which it is equipped S. A law is designed to control the movement of a spacecraft on the trajectory, a nonlinear driving law based on the use of a positively defined Liapunov function; this is expressed in terms of the vectors which represent the deviations of the position and velocity vectors relative to those corresponding to the reference trajectory. From the condition of absolute stability of the automatic control system (stabilization) for the trajectory of S, the simultaneous convergence to zero of the deviations of the position and velocity vectors relative to the position and velocity vectors describing the reference trajectory is ensured. So, the trajectory of S tends to overlap with the reference trajectory. The reference orbit is described by the equation of the orbit in polar coordinates, which is customized for each of the four elliptical orbits, components of the trajectory of the spacecraft (S).

Chapter 4

Chapter four addresses issues of dynamics and control of the relative position and relative attitude of spacecraft in rendezvous missions. The rendez-vous, berthing or docking process consists of performing orbital maneuvers to bring the pursuing vehicle (chaser) close to the target vehicle and then joining (coupling) it [35]. In space missions, when multiple modules, satellites or spacecraft are involved, rendezvous, docking and berthing operations are essential for the in-orbit assembly of such vehicles; supply of space platforms / stations; crew transfer; in-orbit repair of spacecraft; recovery of modules for bringing them to Earth; re-coupling of probes with orbital modules after descending on the surface of a planet.

Models of the dynamics of the chaser vehicle, the target and the relative dynamics of the chaser vehicle to the target vehicle are deduced [2], [86], [91], [93]. A non-linear adaptive control law of the relative position and relative attitude of the chaser vehicle relative to the target vehicle is designed. Then, decoupling the dynamic model of the relative position from that of the relative attitude, two nonlinear adaptive control laws are designed, one for each dynamic. For each of the two control structures, a model is made in the Matlab/Simulink simulation environment and the time characteristics obtained are presented. Then we deduce the equations of the relative motion of the chaser vehicle with respect to the target vehicle, expressed in Cartesian coordinates known as the Tschauner-Hempel equations [112], [110]. At the end of chapter four, the problem of optimal control of the position of the chaser vehicle relative to the target vehicle is addressed using the $H\infty$ method, the method studied and presented in the works [38], [108]. The control law is calculated in such way that a quality square indicator J to have the lowest possible value.

Chapter 5

Chapter five presents the realization of a HW/SW (Hardware/Software) platform with the aim of controlling the trajectory of the simulated model of a launch (carrier) rocket through a numerical controller that implements the adaptive control law based on the concept of dynamic inversion and neural networks designed in the first chapter. The realized platform has two components: a software simulator, developed in the JAVA language, that runs on a PC and implements the dynamics of the launch vehicle (considering disturbances due to the terrestrial gravitational field and the terrestrial atmosphere); a Raspberry Pi SBC (single-board computer) on which the executable generated for the controller implemented in the Simulink environment is loaded. The Orekit open-source library is used to model perturbations, coordinate transformations and define reference systems [78].

Chapter 6

In this final chapter, the general conclusions, the personal contributions and further research developments are presented. The thesis addresses issues related to the automatic control of spacecraft, and, following stages of a space mission (launch, orbit insertion, orbital maneuvers) proposes and presents the design of experimental control laws that are then implemented and tested in the Matlab/Simulink simulation environment. The numerical simulations designed in the first four chapters were performed entirely in the Matlab/Simulink simulation environment. The Eclipse for Java development environment was also used for the platform presented in Chapter Five. Numerical simulation programs designed in Java and Matlab languages are presented in the appendices.

***

I want to thank my family for their moral support, trust and understanding, without which I could not have completed this work.

Special thanks to Prof. PhD. eng. Romulus Lungu, tutor of this thesis and mentor, for the rigorous guidance, permanent support and especially the patience he showed during my doctoral studies.

REFERENCES

[1] ***Le Mouvement Du Vehicle Spatial en Orbite. Cours organise par le Centre National d'etudes spatiales. Toulouse, 1980.

[2] *Ahmed, J., Coppola, V., Berstein, D.S.* Adaptive Asymptotic Tracking of Spacecraft Attitude Motion with Inertia Matrix Identification. Journal of Guidance, Control and Dynamics, Vol. 21, nr.5, 1998, pag. 684-691.

[3] *Aron, I., Lungu, R.* Automate de stabilizare şi dirijare. Editura Enciclopedică, Bucureşti, 1991.

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

[5] *Arthur, E.B.Jr, Yu-chi, Ho.* Applied Optimal Control. Optimization, Estimation and Control. CRC Press, 1975.

[6] *Ashley H.* Engineering Analysis of Flight Vehicles, Dover Publications, New York, 2012.

[7] *Battin, R.H.* An Introduction to the Mathematics and Methods of Aerodynamics. AIAA, Reston, VA, 1999.

[8] *Bauer, S., Krist, S., Compton, W.* Generation of the Ares I-X Flight Test Vehicle Aerodynamic Data Book and Comparison To Flight, 49th AIAA Aerospace Sciences Meeting including the New Horizons and Aerospace Exposition, 4-7 January 2011, Orlando, Florida.

[9] *Bărbulescu L. F.,* ***Buţu, F. A.****, Mamuleanu M. L, Scorţan S. L., Ceolin T., Alacevich R., Grzymisch J.* OrbiPro – a toolbox for accurate orbit propagation. 2018 SpaceOps Conference, 28 May - 1 June 2018, Marseille, France.

[10] *Bărbulescu L.F.,* ***Buţu, F. A.****, Marian M., Stîngă F.*, Estimation of the attitude of a CubeSat under environmental torques. 21st International Conference on System Theory, Control and Computing (ICSTCC) Sinaia 2017, pag. 291-296.

[11] *Bobál, V., Böhm, J., Fessl, J., Machácek, J.* Digital Self-tuning Controllers. Springer-Verlag, London, U.K., 2005.

[12] *Bouadi, H., Wu, H., Mora-Camino, F.* Flight path tracking based-on direct adaptive sliding mode control. IEEE Intelligent Vehicles Symposium, 2011, pag. 25-30.

[13] *Bowring, B.R.* The accuracy of geodetic latitude and height equations. Survey Review, 1985, pag. 202-206.

[14] *Brown, C.D.* Spacecraft Mission Design, Second Edition. American Institute of Aeronautics and astronautics, 1998.

[15] *Bugajski, D.J, Enna, D.F.* Nonlinear Control Law with Application to High Angle of attack Flight. Journal of Guidance, Control and Dynamics, Vol. 15, Nr. 3, 1992, pag. 761-777.

[16] *Butt, A., Popp C. G., Pitts, H. M., Sharp D. J.* NASA Ares I Launch Vehicle Roll and Reaction Control Systems Design Status, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2-5 august 2009, Denver, Colorado.

[17] ***Buţu, F. A.****, Lungu R.* Dynamics modeling and online identification of model parameters for a launch vehicle. In Proc. of New Challenges in Aerospace Sciences International Conference (NCAS), Bucharest, 5-6 november, 2015.

[18] ***Buţu, F. A.****, Lungu R., Bărbulescu L. F.*, Adaptive flight control for a launch vehicle based on the concept of dynamic inversion. In Proc. of 20th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia , October 13-15, 2016, pag. 812-817.

[19] ***Buţu, F. A.****, Lungu, R.* Automatic control of a spacecraft transfer trajectory from an Earth orbit to a moon orbit, U.P.B. Sci. Bull., Series D, Vol. 81 Iss.1, 2019, ISSN 1454-2358.

[20] *Calise, A.J., Rysdyk, R.T.* Nonlinear adaptive flight control using neural networks, Control Systems, IEEE, Volume 18, Issue 6.

[21] *Carter, T. E.* State Transition Matrices for Terminal Rendezvous Studies: Brief Survey and New Example. Journal of Guidance, Control, and Dynamics, Vol. 21, No. 1, 1998, pag. 148–155.

[22] *Calin, S., Belea, C.* Sisteme automate adaptive si optimale. Editura Tehnica, Bucuresti, 1971.

[23] *Christopher E., Sarah K. S.* Sliding Mode Control: Theory And Applications. Taylor & Francis International Ltd., 1998.

[24] *Chwa, D., Choi, J. Y.* Adaptive nonlinear guidance law considering control loop dynamics. IEEE Transactions on Aerospace and Electronic Systems (Volume:39 , Issue: 4)

[25] *Coskun, E.C.* Multistage Launch Vehicle Design with Thrust Profile and Trajectory Optimization. Thesis, Middle East Tehnical University, Ankara, 2014.

[26] *Curtis H.D.* Orbital Mechanics for Engineering Students, Third Edition, Butterworth-Heinemann, 2013.

[27] *Dang, T.* , Discretization of Continuous Controllers, VERIMAG, CNRS (France) (curs online,URL: http://www-verimag.imag.fr/~tdang/DocumentsCours/2013Discretization.pdf)

[28] *Davis, S. R.* Ares I-X Flight Test – The Future Begins Here, AIAA SPACE 2008 Conference & Exposition, 9-11 September 2008, San Diego, California.

[29] *Dorobantu, A. , Seiler, P., Balas, G.* Nonlinear Analysis of Adaptive Flight Control Laws. AIAA Guidance, Navigation and Control Conference, Toronto, Canada, August, 2010.

[30] *Du, W.* Dynamic modeling and Flight Control of Ares-I Crew Launch Vehicle. Thesis, Iowa State University, 2010.

[31] Eclipse IDE, URL: https://www.eclipse.org/downloads/packages/release/kepler/sr1/eclipse-ide-java-developers

[32] ECSS-E-ST-10-04C - Space Engineering - Space Environment, 15/11/2008 [document online] URL: https://www.spacewx.com/Docs/ECSS-E-ST-10-04C_15Nov2008.pdf.

[33] *Erickson, G. E., Wilcox F. J.* Ares I Aerodynamic Testing at the NASA Langley Unitary Plan Wind Tunnel. 49th AIAA Aerospace Sciences Meeting, Orlando, Florida, 2010.

[34] *Evans, R.M.* Satellite orbital control. Thesis, University of Hawai, Manoa, 2008.

[35] *Fehse, W.* Automated Rendezvous and Docking of Spacecraft. Cambridge Aerospace Series, New York, 2003

[36] *Gao, X., Teo, K.L., Duan, G.* Robust H∞ Control of Spacecraft Rendezvous on Elliptical Orbit. Journal of the Franklin Institute, Vol. 349, 2012, pag. 2515-2529

[37] Ghid online - MATLAB and Simulink with Raspberry Pi, URL: https://cdn-learn.adafruit.com/downloads/pdf/how-to-use-matlab-and-simulink-with-raspberry-pi.pdf

[38] *Gu, D., Liu, Y.* Robust Parametric Control of Spacecraft Rendezvous. Hindawi Publishing Mathematical Problems in Engineering, Vol. 2014.

[39] *Haddad, W. M., Chellaboina, V.* Nonlinear Dynamical Systems and Control: A Lyapunov-Based Approach. Princeton, NJ: Princeton University Press, 2008.

[40] *Han, J.* From PID to Active Disturbance Rejection Control. IEEE Trans. Ind. Electron. 56 (3) (2009), pag. 900–906.

[41] *Hang, C., Guo, L.* Control of a Class of Nonlinear Uncertain Systems by Combining State Observers and Parameter Estimators. In Proceedings of the 10th World Congress on Intelligent Control and Automation, Beijing, China, 2012.

[42] *Harkergard, O. Glad, S.T.* A Backstepping Design for Flight Path Angle Control. Sydney, Australia, 2000.

[43] *Hassan, K. Khalil*. Nonlinear Systems. Prentice-Hall Inc., 2000.

[44] *He, S., Lin, D., Wang, J.* Autonomous Spacecraft Rendezvous with Finite Time Convergence. Journal of Franklin Institute, Vol. 352, 2015, pag. 4962-4979.

[45] Hipparchus: a mathematics Library, URL: https://hipparchus.org/

[46] *Isidori, A.* Nonlinear Control Systems. Springer, Berlin, 1995.

[47] Java Platform(JDK): https://www.oracle.com/technetwork/java/javase/downloads/index.html

[48] JFreeChart - Java chart library, URL: http://www.jfree.org/jfreechart/

[49] *Johansson, K.* Orbital mechanics and feedback control. Thesis, Norwegian University of Science and Tehnology, Trondheim, 2005.

[50] *Johnson, E. N., Calise, A. J., Corban, J. E.* Adaptive Guidance and Control For Autonomous Launch Vehicles, Aerospace Conference, 2001, IEEE Proceedings Volume 6, Big Sky, MT.

[51] JSch - Java Secure Channel, URL: http://www.jcraft.com/jsch/

[52] Jzy3d-Open source API for 3d charts, URL: http://www.jzy3d.org/

[53] *Kawaguchi, J.I., Miyazawa, Y., Ninomiya, T.* Flight Control Law Design with Hierarchy-Structured Dynamic Inversion Approch, AIAA Guidance, Navigation and Control Conference Exhibit, 2008.

[54] *Lee, T. , Youdan, K.* Nonlinear Adaptive Flight Control Using Backstepping and Neural Networks Controller. Journal of Guidance, Control and Dynamics, Vol. 24, July-August, 2001.

[55] *LeFevre, B. D., Jha, R.,* Hybrid adaptive ascent flight control for a flexible launch vehicle. Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering 225(8):851-862, July 2011.

[56] *LeFevre, B.D.* Hybrid adaptive ascent flight control for a flexible launch vehicle, Thesis, Clarkson University, 2010.

[57] *Liang, J., Ma, O.* Angular Velocity Tracking for Satellite Rendez-vous and Docking. Journal Acta Astronautica, Vol. 69, 2011, pag. 1019-1028.

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

[59] *Lungu, M.* Sisteme de conducere a zborului. Editura Sitech, Craiova, 2008.

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

[61] *Lungu, M., Lungu, R.,* ***Buţu, F. A.*** Reduced-order Multiple Observer with Application to the State Estimation of a Controlled Generic Reentry. 2018 IEEE International Systems Engineering Symposium (ISSE), Rome, 2018, pag. 1-6

[62] *Lungu, R.* Automatizarea aparatelor de zbor. Editura Universitaria, Craiova, 2000

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

[64] *Lungu, R.* Sisteme de dirijare aerospaţiala. Editura Sitech, Craiova, 2002.

[65] *Lungu, R.,* ***Buţu F. A.****, ş.a.*, Contract de cercetare Platforma hardware bazata pe utilizarea retelelor neuronale pentru vehicule spatiale sub-orbitale si orbitale. PN III, NR. 232PED/2017.

[66] *Lungu, R.,* ***Buţu, F. A.****, Lungu, M.* Automatic Control of Space Vehicles' Orbit around Earth. 2018 IEEE International Systems Engineering Symposium (ISSE), 1-3 Oct. 2018, Rome, Italy, 2018, pag. 1-6.

[67] *Lungu, R.,* ***Buţu, F. A.****, Lungu, M.* Flight control of a launch vehicle using the hierarchical structured dynamic inversion with three time-scales, 2018 IEEE International Systems Engineering Symposium (ISSE), Rome, 2018, pag. 1-5.

[68] *Lungu, R.,* ***Buţu, F. A.****, Lungu, M. Sliding Mode Control of Launch Vehicles' Flight Path Slope Angle*. 2018 26th Mediterranean Conference on Control and Automation, June 19-22, 2018, Zadar, Croatia, pag. 1-6.

[69] *Lungu, R., Tudosie, Al., Dinca, L.* Mecanica fluidelor si termodinamica tehnica. Editura Sitech, Craiova, 2004.

[70] *Luo, J., Gong, B., Yuan, J., Zhang, Z.* Angles-only Relative Navigation and Closed-loop Guidance for Spacecraft Proximity Operations. Journal Acta Astronautica, Vol. 128, 2016, pag. 91-106

[71] *Marinescu, Al., Staicu, St.* Elemente de mecanica zborului spațial. Editura Tehnică, Bucureşti, 1997.

[72] *Markley, F. L., Crassidis, J. L.* Fundamentals of Spacecraft Attitude Determination and Control, Springer, 2014.

[73] *Meng, Y., Chen, Q., Ni, Q.* A new Geometric Guidance Approach to Spacecraft Near-distance Rendez-vous Problem. Journal Acta Astronautica, Vol. 129, 2016, pag. 374-383.

[74] *Menon, P.K. Igravaspu, A. Ohlmeyer, E.J.* Nonlinear Missile Autopilot Design using Time-scale Separation. Proceedings of the AIAA Guidance, Navigation and Control Conference, In proceedings, pag. 1791-1803, 1997.

[75] *Ming-Da, M., Xian-Din, Z., Gung-Ren, D.* Optimal Two-Impulse Orbital Transfer Between Coplanar Orbits. In Proc. Of the 29th Chinese Control Conference, July 29-31, 2010, Beijing, China.

[76] *Miyzawa, Y., Motoda, T. Izumi, T., Hato, T.* Longitudinal Landing Control Law for an Autonomous Reentry Vehicle. Journal of Guidance, Control, and Dynamics, Vol 22, Nr. 6, pag. 791 – 800.

[77] *Niţă, M.* Dinamica zborului spaţial. Editura Academiei Române, Bucureşti 1964.

[78] Orekit-an accurate and efficient core layer for space flight dynamics applications, URL: https://www.orekit.org/

[79] Philip, N.K., Ananthasayanam, M.R. Relative Position and Attitude Estimation and Control Schemes for the Final Phase of an Autonomous Docking Mission of Spacecraft. Journal Acta Astronautica, Vol. 52, 2003, 511-522.

[80] *Qi, Y., Jia, Y.* Constant Thrust Fuel-optimal Control for Spacecraft Rendezvous. Advances in Space Research, Vol. 49, 2012, pag. 1140-1150.

[81] Raspberry Pi Support from Simulink, URL: https://www.mathworks.com/hardware-support/raspberry-pi-simulink.html.

[82] *Sahjendra, N. , Singh, M.* Variable Structure and Nonlinear Adaptive Flight Path Control. In Proceedings of the American Control Conference, Anchorage, May, 2002.

[83] *Sharma, M.* Flight Path Angle Control via Neuro-Adaptive Backstepping. In Proceedings AIAA Guidance, Navigation and Control Conference, Monterey, Canada, August 2002.

[84] *Sharma, M., Calise, A. J.* Neural-Network Augmentation of Existing Linear Controllers, Journal of Guidance Control and Dynamics, Vol. 28, No. 1, January-February 2005.

[85] *Sidi, M. J.* Spacecraft Dynamics and Control. Cambridge University Press, 2000.

[86] *Sidi, M.J.* Spacecraft Dynamics and Control a Practical Engineer Approach. New York, Cambridge University Press, 1997

[87] Simulink Support Package for Raspberry Pi Hardware, URL: https://www.mathworks.com /help/supportpkg/raspberrypi/

[88] *Stengel, R. F.* Optimal Control And Estimation, Dover Publications, New York 1994.

[89] *Stuelpnagel, J.* On the Parametrization of the Three-dimensional Rotation Group, SLAB Review, Vol. 6, Nr. 4, 1964.

[90] *Sun, L., Huo, W.* Robust Adaptive Control of Spacecraft Proximity Maneuvers Under Dynamic Coupling and Uncertainty. Advances in Space Research, Vol. 56, 2017, pag. 2206-2217

[91] *Sun, L., Huo, W.* Robust Adaptive Relative Position and Attitude Synchronization for Spacecraft Rendezvous. Journal Aerospace Science and Technology, Vol. 41, 2015, pag. 28-35.

[92] *Sun, L., Huo, W., Jiao, Z.* Adaptive Nonlinear Robust Relative Pose Control of Spacecraft Autonomous Rendezvous and Proximity Operations. Journal ISA Transactions, Vol. 67, 2017, pag. 47-55.

[93] *Sun, L., Huo, W., Jiao, Z.* Robust Adaptive Relative Position and Attitude Control for Spacecraft Autonomous Proximity, Journal ISA Transaction, Vol. 63, 2016, pag. 11-19.

[94] *Teodorescu, C., Ionescu, D., Zăgănescu, Fl.* Sateliţi artificiali la sfârşit de mileniu. Editura Ştiinţifică şi Enciclopedică, Bucureşti, 1988.

[95] *Thomson, W.T.,* Introduction to Space Dynamics, Dover Publications, 1986.

[96] *Tsiotras, P.* Stabilization and Optimality Results for the Attitude Control Problem. Journal of Guidance, Control and Dynamics, Vol. 19, nr. 4, 1996, pag. 772-779.

[97] *Tudosie, A. N.,* ***Buţu, F. A.*** Aircraft landing with decelerated approach (Longitudinal movement model). 2016 International Conference on Applied and Theoretical Electricity (ICATE), Craiova, Romania, 6-8 October, 2016, pag. 1-6.

[98] U.S. Standard Atmosphere 1976, URL: http://www.pdas.com/atmosTable1SI.html, http://www.pdas.com/atmosTable2SI.html

[99] *Vallado, D.,* Fundamentals of Astrodynamics and Applications. 4th ed., Microcosm Press, US, 2007.

[100] *Van Der Ha, J.C., Janssens, F.L.* Jet-Damping and Misalignment Effects During Solid-Rocket-Motor Burn, Journal of Guidance, Control, and Dynamics, Vol. 28, No. 3 (2005), pag. 412-420.

[101] *Voicu, S. C.,* ***Buţu, F. A.*** H-Infinity Design for Automatic Landing System. International Journal of Modeling and Optimization, Vol. 7, No. 3, June 2017, pag. 173-178.

[102] *Wang, Q., Duan, G.* Robust Global Stabilization of Spacecraft Rendezvous System via Gain Scheduling. International Journal of Automation and Computing, Vol. 11, August 2014, pag, 426-433

[103] *Westervelt, E.R., Grizzle J.W., Chevallereau, C., Choi, J.H., Morris, B.* Feedback Control of Dynamic Bipedal Robot Locomotion. CRCPress, BocaRaton, FL, USA, 2007.

[104] *Wie, B.* Space Vehicle Dynamics and Control, AIAA Educations Series, 1998.

[105] *Wiesel, W.E.* Spaceflight Dynamics, Third Edition, McGraw-Hill Series in Aeronautical and Aerospace Engineering, 2010.

[106] *Wittenmark, B. , Åström K. J.,* Computer-controlled Systems: Theory and Design. Dover Publications, Third edition, December 14, 2011.

[107] *Wu, J., Liu, K., Han, D.* Adaptive Sliding Mode Control for Six-DOF Relative Motion of Spacecraft with Input Constraint. Journal Acta Astronautica, Vol. 87, 2013, pag. 64-76

[108] *Wu, S., Zhou, W., Tan, S., Wu, G.* Robust H∞ Control for Spacecraft Rendezvous with a Noncooperative Target. The Scientific World Journal, Vol. 2013

[109] *Xia, K., Huo, W.* Robust Adaptive Backstepping Neural Networks Control for Spacecraft Rendezvous and Docking with Input Saturation. Journal ISA Transaction, Vol. 62, 2016, pag. 249-257

[110] *Xu, L., Hu, Y., Jiang, T.* Adaptive Control and Orbit Determination for Elliptical Rendezvous. Journal Acta Astronautica, Vol. 127, 2016, pag. 587-592

[111] *Xue, W.,Huang, Y.* Comparison of the DOB Based Control, a special kind of PID Control and ADRC. In Proceedings of the 2011 American Control Conference, San Francisco, USA, 2011, pag. 4373–4379

[112] *Yamanaka, K., Ankersen, F.* New State Transition Matrix for Relative Motion on an Arbitrary Elliptical Orbit. Journal of Guidance, Control and Dynamics, Vol. 25, No. 1, 2002, pag. 60–66.

[113] *Yucelen, T.,Calise, A.J.* Derivative-Free Model Reference Adaptive. Control. Journal of Guidance, Control and Dynamics, Vol. 34, No. 4, 2011, pag. 933–950.

PUBLICATIONS OF THE AUTHOR DURING THE PHD STAGE

1. **Buţu, F. A.**, Lungu R. *Dynamics modeling and online identification of model parameters for a launch vehicle*. The 2nd edition of New Challenges in Aerospace Science International Conference, NCAS 2015, Bucharest, Romania, 5-6 November 2015.
2. **Buţu, F. A.**, Lungu R., Bărbulescu L. F., *Adaptive flight control for a launch vehicle based on the concept of dynamic inversion*. In Proc. of 20th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia, October 13-15, 2016, pp. 812-817. *Database: IEEE Xplore, Web of Science Core Collection*.
3. **Buţu, F. A.**, Lungu, R. *Automatic control of a spacecraft transfer trajectory from an Earth orbit to a moon orbit*, U.P.B. Sci. Bull., Series D: Mechanical Engineering, Vol. 81 Iss.1, 2019, ISSN 1454-2358.
4. Tudosie, A. N., **Buţu, F. A.** *Aircraft landing with decelerated approach (Longitudinal movement model)*. 2016 International Conference on Applied and Theoretical Electricity (ICATE), Craiova, Romania, 6-8 October, 2016, pp. 1-6. *Database: IEEE Xplore, Web of Science Core Collection*.
5. Bărbulescu L.F., **Buţu, F. A.**, Marian M., Stîngă F., *Estimation of the attitude of a CubeSat under environmental torques*. 21st International Conference on System Theory, Control and Computing (ICSTCC) Sinaia 2017, pp. 291-296. *Database: IEEE Xplore, Web of Science Core Collection*.
6. Voicu, S. C., **Buţu, F. A.** *H-Infinity Design for Automatic Landing System*. International Journal of Modeling and Optimization, Vol. 7, No. 3, June 2017, pp. 173-178.
7. Bărbulescu L. F., **Buţu, F. A.**, Mamuleanu M. L, Scorţan S. L., Ceolin T., Alacevich R., Grzymisch J. *OrbiPro – a toolbox for accurate orbit propagation*. 2018 SpaceOps Conference, 28 May - 1 June 2018, Marseille, France. *Database: AIAA Aerospace Research Central*
8. Lungu, M., Lungu, R., **Buţu, F. A.** *Reduced-order Multiple Observer with Application to the State Estimation of a Controlled Generic Reentry*. 2018 4th IEEE International Systems Engineering Symposium (ISSE), Rome, 2018, pp. 1-6. *Database: IEEE Xplore, Web of Science Core Collection*.
9. Lungu, R., **Buţu, F. A.**, Lungu, M. *Automatic Control of Space Vehicles' Orbit around Earth*. 2018 4th IEEE International Systems Engineering Symposium (ISSE), 1-3 Oct. 2018, Rome, Italy, 2018, pp. 1-6. *Database: IEEE Xplore, Web of Science Core Collection*.

10. Lungu, R., **Buţu, F. A.**, Lungu, M. *Flight control of a launch vehicle using the hierarchical structured dynamic inversion with three time-scales*, 2018 4th IEEE International Systems Engineering Symposium (ISSE), Rome, 2018, pp. 1-5. *Database: IEEE Xplore, Web of Science Core Collection*.

11. Lungu, R., **Buţu, F. A.**, Lungu, M. *Sliding Mode Control of Launch Vehicles' Flight Path Slope Angle*, 2018 26th Mediterranean Conference on Control and Automation, June 19-22, 2018, Zadar, Croatia, pp. 553-558. *Database: IEEE Xplore, Web of Science Core Collection*.