DYNAMICS AND CONTROL OF SPACE SYSTEMS DyCoSS'2017

Front Cover Illustration:

The illustration represents the space view of the Earth, International Space Station (ISS) and other satellites in low-earth orbits. Credit: Academy of Engineering, RUDN University.

Third IAA Conference on DYNAMICS AND CONTROL OF SPACE SYSTEMS 2017

Volume 161
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Yury N. Razoumny
Filippo Graziani
Anna D. Guerman
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FOREWORD

This volume of the Series *Advances in the Astronautical Sciences* is dedicated to the third IAA Conference on Dynamics and Control of Space Systems – DyCoSS'2017 held in Moscow (Russia), March 30 – June 1, 2017 and hosted by RUDN University – the only university in the world that unites students from more than 150 countries, the meeting point for different cultures and viewpoints. Nowadays RUDN University with its Training Mission Control Center and multiple laboratory infrastructure is an expanding platform for space education, a place for research and discussion connected with Russian space industry enterprises including Russian Mission Control Center in Korolev City, Moscow Region used for control of International Space Station together with Mission Control Center at NASA's Johnson Space Center, Houston, Texas.

The Conference was promoted by the International Academy of Astronautics (IAA) with the cooperation of the American Astronautical Society (AAS) and organized by RUDN University. The aim was to join specialists in Astrodynamics, Space Flight Mechanics, and Space Structures.

The Conference Chairs were Yury Razoumny (Russia), Filippo Graziani (Italy), Anna Guerman (Portugal), and Jean-Michel Contant (France) and the International Program Committee was formed by:

- Brij Agrawal, USA
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The local organization was supported by the RUDN University Organizing Committee:

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The program contained four parallel sessions alternated with eight highlighted lectures on the hottest topics of space research. The 3d IAA Conference on Dynamics and Control of Space Systems attracted an unexpectedly large number of scientists from all over the world: more than 250 participants from 19 countries attended and provided an interesting forum for research in the field.

The Opening Ceremony began with a talk "The International Academy of Astronautics and Astrodynamics: Past, Present and Future," presented by Vice-President of International Academy of Astronautics Prof. Anatoly Perminov. The ceremony was continued by welcome speeches of Vice-President of American Astronautical Society Prof. David Spencer and Rector of RUDN University Prof. Vladimir Filippov and accomplished by a concert performance consisting of folk songs and dances presented by RUDN University students from different countries.

In the inauguration speech, Vice-President of International Academy of Astronautics Prof. Anatoly Perminov, underscored the large number of high-quality papers submitted. These papers were organized in 8 thematic sessions. The final program consisted of more than 120 presentations, even though during the conference only 82 papers were actually presented by the authors, while others were late withdrawals or "no shows." The present volume includes only the papers that were discussed during the DyCoSS'2017 sessions.

The work of thematic sessions of DyCoSS'2017 began on May 30 and continued to the afternoon of June 1. These sessions included presentations on Satellite Constellation and Formation Flying, Spacecraft Guidance, Navigation and Control, Attitude Dynamics and Control, Attitude Sensors and Actuators, Orbital Dynamics and Determination, Mission Design and Optimization, Space Structures and Tethers. The Highlight Lectures were presented by Prof. Tetsuo Yasaka, Kyushu University, Japan, Prof. David Spencer, Penn State University, USA, Prof. Arun Misra, McGill University, Canada, Prof. Kathleen Howell, Purdue University, USA, Prof. Roberto Furfaro, University of Arizona, USA, Prof. Alexander Yefremov, RUDN University, Russia, Prof. Antonio Prado, National Institute for Space Research, Brazil, Prof. Brij Agrawal, Naval Postgraduate School Monterey, USA. On June 1–2 the participants of the conference visited Russian Space Mission Control Center in Korolev City, Moscow Region and took part in Boat Tour on Moscow River.

The Conference contributed to intensive discussions of the modem research, dissemination of the up-to-date information in the area and better contacts between the members of Space scientific community. A series of DyCoSS Conferences found its place in the tight calendar of the events in Space Systems as a stand-alone conference for Astrodynamics. We are confident that such an event will inspire a stronger cooperation in the space community and will be a research incentive in the Space field panorama.

Nothing of the above-mentioned would have been possible without the great effort of many colleagues. We are grateful to all members of the International Program Committee, the Local Organizing Committee and RUDN University. We appreciated very much the dedication of the participants of DyCoSS'2017 (both the authors of papers and the audience in general) that made possible fruitful discussions at the conference sessions and beyond. Finally, we would like to express our gratitude to Mr. Robert Jacobs for his continuous support and to Univelt, Inc., for publishing this volume.

DyCoSS'2017 Co-Chairs:
Prof. Yury Razoumny
Prof. Filippo Graziani
Prof. Anna D. Guerman
Dr. Jean-Michel Contant

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Arun Misra, Canada
Antonio Bertachini Prado, Brazil
Renuganth Varatharajoo, Malaysia

IAA-AAS-DyCoSS3-038
AAS 17-851

SATELLITE DYNAMICS UNDER THE INFLUENCE OF GRAVITATIONAL AND DAMPING TORQUES

Vasily A. Sarychev[*] and Sergey A. Gutnik[†‡]

In this paper the dynamics of the rotational motion of a satellite, moving in the central Newtonian force field in a circular orbit under the influence of gravitational and active damping torques, depending on the projections of the angular velocity of the satellite is investigated. The main attention is given to study the necessary and sufficient conditions for asymptotic stability of satellite's equilibria for special case, when the principal axes of inertia of the satellite coincide with the axes of the orbital coordinate system.

[View Full Paper]

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IAA-AAS-DyCoSS3-110
AAS 17-852

FUZZY SWITCH-GAIN SLIDING MODE CONTROL FOR SPACECRAFT COMBINED ATTITUDE AND SUN TRACKING SYSTEM

Yew-Chung Chak* and Renuganth Varatharajoo†

This paper proposes an attitude tracking scheme using the fuzzy sliding mode control (FSMC) for the combined attitude and sun tracking system. A fuzzy logic system is constructed to replace the static switch-gain to reduce the chattering. Simple fuzzy rules are designed to approximate the switch-gain where it emulates the disturbance. This enables the switch-gain to be kept as low as possible to reduce the chattering without compromising its robustness. Numerical results demonstrate that the chattering is attenuated greatly using FSMC and the spacecraft achieves the attitude and sun tracking with a very good robustness to external disturbance. [View Full Paper]

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IAA-AAS-DyCoSS3-014
AAS 17-853

ATTITUDE AND VIBRATION CONTROL FOR A FLEXIBLE SPACECRAFT WITH DOUBLE-GIMBAL VARIABLE-SPEED CONTROL MOMENT GYROS

Takahiro Sasaki,[*] Takashi Shimomura,[†] Sam Pullen[‡] and Hanspeter Schaub[§]

The attitude and vibration control of a flexible spacecraft with two parallel double-gimbal variable-speed control moment gyros (DGVSCMGs) is considered. The coupled nonlinear equations of motion create a complex challenge in a pointing control development. First a Gain-Scheduled (GS) controller for a 3-axis attitude control is designed by the post-guaranteed linear matrix inequalities (LMIs) method with $\mathcal{H}_2/\mathcal{H}_\infty$ constraints. Next an $\mathcal{H}_2/\mathcal{H}_\infty$ controller for vibration control is designed to attain both attitude and vibration control at the same time. The two controllers are combined using the dynamic inversion (DI) technique. Finally, the effectiveness of the proposed combined controller is demonstrated through a numerical example. [View Full Paper]

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IAA-AAS-DyCoSS3-017
AAS 17-854

GLOBAL AND ROBUST ATTITUDE CONTROL OF A LAUNCH VEHICLE IN EXOATMOSPHERIC FLIGHT*

Fabio Celani†

The goal of this research is to design global attitude control systems for launch vehicles in exoatmospheric flight. An attitude control system is global when it guarantees the vehicle converges to the desired attitude regardless of its initial condition. Global controllers are important since they allow to perform large angle maneuvers using simpler algorithms with respect to several local controllers patched together. It is also required that the designed autopilots are robust, which means global convergence must be achieved despite uncertainties in the parameters of the vehicle. Two designs are carried out. In the first one possible delays introduced by the actuator are neglected. The first design is performed by using a Lyapunov approach, and the obtained autopilot is a standard proportional-derivative controller. In the second one, the effects of the actuator are considered. Then, the design is based on a robust backstepping approach which leads to a memoryless nonlinear feedback of attitude, attitude-rate, and engine's deflection angle. Both autopilots are validated in a case study. [View Full Paper]

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IAA-AAS-DyCoSS3-066
AAS 17-855

MAGNETIC SLIDING MODE ATTITUDE CONTROLLER DESIGN WITH MOMENTUM EXCHANGE AUGMENTATION

Ahmet Sofyalı* and Elbrous M. Jafarov†

A magnetic sliding mode attitude controller is augmented by momentum exchange to improve the steady state performance of the control system. The sliding mode controller is designed based on the equivalent control approach and by using a novel sliding surface vector that is proposed specifically to the purely magnetic attitude control problem. The augmentation is fulfilled by making a reaction wheel triad to produce only the component of the continuous equivalent control vector that is along the local geomagnetic field vector. The result is a control system that is still robustly stable and has two times less steady state er-ror with very little additional energy consumption. [View Full Paper]

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IAA-AAS-DyCoSS3-030
AAS 17-856

CUBESAT ATTITUDE CONTROL BASED ON HARD DISK DRIVE COMPONENTS – THEORY AND PRACTICE

Liran Sahar,[*] Eviatar Edlerman,[†] Hovhannes Agalarian,[‡] Vladimir Balabanov[§] and Pini Gurfil[**]

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To control the rotational state of nanosatellites, miniaturized reaction wheels have been widely used. Miniaturized reaction wheels are manufactured by several companies, and can be found in multiple CubeSat missions. These reaction wheels have space heritage and good performance, but they are extremely costly. A typical price of a reaction wheel ranges from 12,000 to 20,000 USD. This poses a major problem to most CubeSat developers. We developed a cost-effective alternative to existing reaction wheels, which reduces the cost of a unit to about 300 USD. The idea is to use hard disk drive (HDD) components as reaction wheels for CubeSats. HDD-based reaction wheels are much more affordable and provide similar performance to commercial systems. Analysis and experiments have been performed in order to validate the compatibility of the HDD-based wheel to the space environment. [View Full Paper]

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IAA-AAS-DyCoSS3-080
AAS 17-857

A SOFTWARE TOOL FOR THE ESTIMATION OF CHEMICAL THRUSTERS PLUME IMPINGEMENT-RELATED DISTURBANCE TORQUES ON SPACECRAFT AXES

Augusto Montani,[*] Michelangelo L'Abbate,[†] Andrea Marchetti,[†] Fabio Di Giorgio,[†] Andrea Adriani[†] and Alberto Ritorto[†]

An original 3D mathematical model to preliminarily assess disturbances produced by the interaction of thruster's plume with spacecraft's surfaces has been developed and implemented in the Matlab computing environment. The plume flow in the far-field is approximated with radial flow and the density distribution is evaluated by means of L. Roberts and J.C. South analytical method (NASA, Langley Research Center). Newtonian theory is applied to compute the pressure on impinged bodies so that its dependence on the angle of attack is taken into account. The spacecraft geometric representation (CAD model) is directly fed to the program and the plume-impinged surfaces are discretized with prescribed resolutions. The overall disturbance torque applied to the spacecraft is obtained by summing up elemental torques, in turn given by the normal forces exerted on each surface element. Simulation results have been compared to spacecraft data telemetries showing a general compliance and agreement in both qualitative and quantitative terms. Validation of the model is still ongoing. [View Full Paper]

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IAA-AAS-DyCoSS3-136
AAS 17-858

FEEDBACK LINEARIZATION FOR SPACECRAFT ATTITUDE CONTROL WITH HARDWARE-IN-THE-LOOP SIMULATIONS

M. Navabi,[*] M. R. Hosseini[†] and M. Barati[‡]

Feedback linearization is among the nonlinear control theories based on a state feedback of dynamics system nonlinearities which in turns linearizes the system. Therefore, linear control methods might be exploited in designing the nonlinear feedback linearization control (FLC). In this paper, feedback linearization is used to control the attitude of spacecraft by means of reaction wheel assemblies. Simulation results demonstrate the more effectiveness of this method over solely employing linear methods such as PID and LQR. Particularly, the control effort was significantly optimized using FLC. Furthermore, the designed controller is implemented on an experimental 3DOF hardware-in-the-loop attitude control platform in order to demonstrate the applicability of this method. The platform consists of low friction ball bearing gimbals providing 3 degrees of freedom for educational research. A configuration of orthogonal reaction wheel assemblies is used and a real-time communication is provided for transmitting control commands and monitoring the states. The simulation results are presented for a large angle attitude maneuver.

[View Full Paper]

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IAA-AAS-DyCoSS3-026
AAS 17-859

ATTITUDE MOTION OF LARGE SPACE DEBRIS IN SUN-SYNCHRONOUS ORBITS: SIMULATION OF LONG-TERM EVOLUTION

S. S. Efimov,[*] D. A. Pritykin[†] and V. V. Sidorenko[‡]

Sun-synchronous orbits (SSO) are known for the highest density of space debris population. For this reason, these orbits are often discussed in active debris removal (ADR) projects, which are to reduce pollution of the near-Earth environment. ADR missions planning is hardly possible without at least an approximate idea about the attitude dynamics of candidate objects. We have conducted a study to establish the general patterns of large debris rotational motion evolution in SSO and obtain the typical values of its parameters.

Prior research indicates that attitude motion of debris objects in SSO is influenced mainly by the gravity gradient torque and the torque due to eddy currents induced by geomagnetic field. Internal energy dissipation via deformable elements and residual propellant should also be taken into account as it results in transformation of arbitrary initial motion to "flat" rotation.

Qualitatively the rotational motion evolution can be divided into three stages: transition to "flat" rotation, exponential decay and the gravitational capture. During the first relatively brief stage, the motion is primarily influenced by internal dissipation. In the second stage angular velocity decays exponentially due to eddy currents. When the object's angular velocity becomes comparable to the orbital angular velocity, the gravitational capture stage takes place exhibiting chaotic dynamics and resulting typically in the gravitational stabilization of the object. During the stage of exponential deceleration the rotation axis leans towards the orbital plane. For retrograde spins this results in capture of angular velocity vector in oscillations about the direction to the south celestial pole. This effect is the direct consequence of SSO precession.

We use general formula for the torque due to eddy currents, which includes terms describing the influence of orbital motion. For fast rotations these terms are small and often neglected. However, our research shows that even for relatively large angular velocities (20–30 times greater than the orbital angular velocity) these terms can cause significant changes in the rotational axis direction for prograde spins. Furthermore, they affect final stages of rotational motion evolution and give rise to a stationary regime alternative to gravitational stabilization. In this regime the object rotates about the orbital plane normal with angular velocity equal to 1.8 of the orbital angular velocity.

All stages of rotational motion evolution were studied analytically and in numerical experiments, for which we chose Ariane 4 H10 stage and defunct satellites of SPOT family.

This work was supported by RFBR (grant 17-01-00902). [View Full Paper]

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ORBITAL DYNAMICS AND DETERMINATION

Session Chairs:
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Kathleen Howell, U.S.A.
Anna D. Guerman, Portugal
Giovanni Palmerini, Italy

IAA-AAS-DyCoSS3-144
AAS 17-860

TRAJECTORY DYNAMICS ANALYSIS OF REUSABLE SUBORBITAL LAUNCH VEHICLE FOR TOURISM

Jeng-Shing (Rock) Chern* and Yi-Wei (Eva) Chang†

Currently, there are three major reusable suborbital launch vehicles (RSLVs, or the so-called spaceplanes in many documents) developed for suborbital scientific research and suborbital space tourism (SST): Virgin Galactic's SpaceShipTwo (SS2), XCOR's Lynx and Blue Origin's New Shepard. Of which, SS2 and Lynx are the horizontal-takeoff-horizontal-landing (HTHL) type and New Shepard is the vertical-takeoff-vertical-landing (VTVL) type. Therefore, the commercial operations of SST might be expected to take place within a few years in the future. No matter the RSLV belongs to HTHL or VTVL type, both use rocket engine as propulsion system. As such, the trajectory dynamics and characteristics are very different from aviation airplane. The major purposes of this paper are to analyze the trajectory dynamics by using the characteristics of RSLV, and to make comparison with those of the aviation airplane. Analysis results show that the high-g acceleration is about 10 times and the high-g deceleration is about 15 times of airplane. Also, there is a weightlessness flight phase for several minutes. Besides, the levels of noise and vibration are very high when the rocket engine is working. [View Full Paper]

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IAA-AAS-DyCoSS3-102
AAS 17-861

FRACTAL PYRAMID CONTROLLING ORIENTATION AND VELOCITY OF SPACECRAFT

Alexander P. Yefremov*

Quaternion based math tool of spacecraft reorientation is extended by admitting imaginary rotation parameters, thus involving hyperbolic functions. This new tool is proved to simultaneously reorient the spacecraft and to accelerate it, the kinematics automatically described as relativistic. Pre-geometric image of the tool is modeled by a tilted and distorted fractal pyramid. [View Full Paper]

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IAA-AAS-DyCoSS3-058
AAS 17-862

DYNAMICS OF A MASSIVE POINT ABOUT A UNIFORMLY ROTATING, TWO-LOBE CELESTIAL BODY

Alexander A. Burov,[*] Anna D. Guerman,[†] Ivan I. Kosenko[‡] and Vasily I. Nikonov[§]

Problem of motion of a massive particle in a field of attraction of a homogeneous dumb-bell is considered. It is assumed that the dumb-bell comprises two balls intersecting each other. The balls are not assumed being identical. An approximate expression for the Newtonian potential is written down. Relative equilibria of the particle ("libration points") are investigated within the assumption on uniform rotation of the dumb-bell.

[View Full Paper]

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IAA-AAS-DyCoSS3-129
AAS 17-863

SPACECRAFT THRUST VECTOR CONTROL DURING LANDING ON THE MOON SURFACE

Maksim M. Matyushin,[*] Vladimir M. Ovechko,[†] Yury N. Razoumny,[‡] Oleg P. Skorobogatov,[§] Daria D. Tyurina[**] and Irina S. Baranova[††]

The problem of optimal control of the thrust vector of a spacecraft power engine, making a decay and soft landing from the circular satellite orbit of the Moon to its surface, is considered. The maximum principle of L. S. Pontryagin was used to determine the control structure. An approach has been developed to determine the optimal thrust control programs for the power engine. The results of the trajectory calculation of a spacecraft landing on the lunar surface are presented. [View Full Paper]

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IAA-AAS-DyCoSS3-127
AAS 17-864

RADIOASTRON ORBIT DETERMINATION AND EVALUATION OF ITS RESULTS USING CORRELATION OF SPACE-VLBI OBSERVATIONS

Mikhail V. Zakhvatkin,[*] Andrey S. Andrianov,[†] Vladimir I. Kostenko,[‡] Yuri Y. Kovalev,[§] Sergey F. Likhachev,[**] Alexey G. Rudnitsky,[†] Victor A. Stepanyants,[††] Andrey G. Tuchin,[‡‡] Petr A. Voytsik[†] and Grigoriy S. Zaslavskiy

The paper describes Radioastron orbit determination (OD) method implemented at Keldysh Institute of Applied Mathematics. The method utilizes both observations from ground based stations and additional information obtained via telemetry channel including the data on thrusters firings, rotation of reaction wheels and current attitude of the spacecraft. To evaluate the orbital accuracy we use residual delays parameters obtained by the Astro Space Center on processing of the Radioastron observational data. Such data after excluding instrumental effects contains information about the orbital errors projected on the direction to the observed source. [View Full Paper]

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IAA-AAS-DyCoSS3-046
AAS 17-865

THREE-BODY PROBLEM FOR THE EARTH-MOON SYSTEM UNDER PHOTO-GRAVITATIONAL INFLUENCE OF THE SUN

Tatiana Salnikova,* Sergey Stepanov† and Anna Shuvalova‡

Polish astronomer K. Kordylewski has discovered the clouds of interplanetary dust in the neighborhood of the triangular libration points of the Earth-Moon system. More than 60 years after the first observation the existence of these elusive clouds is still disputed. Due to the unavoidable perturbations, such that the influence of the Sun, the triangular libration points have to be unstable. In the perturbed three body problem, we show the possibility of the existence of four dust clouds, moving along the stable periodical orbits, capturing the Lagrange libration points, and discuss the best conditions to observe them.
[View Full Paper]

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IAA-AAS-DyCoSS3-125
AAS 17-866

NEAR RECTILINEAR HALO ORBITS AND THEIR APPLICATION IN CIS-LUNAR SPACE

Emily M. Zimovan,[*] Kathleen C. Howell[†] and Diane C. Davis[‡]

Near Rectilinear Halo Orbits (NRHOs), a subset of the L_1 and L_2 halo orbit families, are strong candidates for a future inhabited facility in cis-lunar space. Characteristics of the NRHOs, including stability and eclipsing properties, are presented along with a strategy to detect real-time diverging behavior. To be useful to future missions, the accessibility of these orbits must also be addressed. Transfer options from the NRHOs to the Distant Retrograde Orbits (DROs) are investigated. Additionally, a brief overview of past NRHO stationkeeping analysis is included. [View Full Paper]

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ZERO VELOCITY CURVES OF A BINARY ASTEROID SYSTEM BASED ON THE CIRCULAR FULL RESTRICTED THREE-BODY PROBLEM

Thais C. Oliveira[*] and Antonio F. B. A. Prado[†]

This paper aims to find the Lagrangian points and the zero velocity curves in a circular full restricted three-body problem. This paper also approaches the method to compute the stability of these equilibrium points and to find periodic orbits in the binary system. It considers different shapes, sizes and mass distributions of the binary asteroid system.

[View Full Paper]

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MAPPING TRAJECTORIES FOR A SPACECRAFT TO HIT AN ASTEROID TO AVOID A COLLISION WITH THE EARTH

Geraldo Magela Couto Oliveira,[*] Antonio F. Bertachini de A. Prado,[†] Diogo M. Sanchez,[‡] Jorge M. Nascimento[§] and Vivian M. Gomes[**]

The study of asteroids has revealed much about these small rock-formed bodies compared to the planets, which like them also orbit around the Sun. But, although these bodies have masses smaller than the Moon, they present serious dangers, given the fact that many of them have already collided with the Earth in the past, and many others have the probability to collide in the future. Therefore, these are the reasons that lead scientists to promote the study of such celestial bodies, from the point of view of their physical characteristics and the point of view of its dynamics, which can provide the information of how many and when they will collide with the Earth. In recent years, several missions have been proposed to reach asteroids and comets in the Solar System, such as Aster, Dawn, Marco Polo-R, NEAR Shoemaker, Osiris-Rex and Rosetta. The bodies that are target of these missions are very important in terms of science, because they may keep information related to the origin of the Solar System. Another key point is that there is a growing interest in the problem of collision avoidance between an asteroid and the Earth. It means that it is very important to find trajectories to those bodies, which is the main objective of this work. Such trajectories can be used to collision avoidance missions.

[View Full Paper]

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ORBITAL AND ATTITUDE COUPLED DYNAMICS OF A SPACECRAFT AROUND AN ASTEROID

Isabelle Jean,[*] Arun K. Misra[†] and Alfred Ng[‡]

Because of their irregular shape and rotations, asteroids offer a more complex gravitational environment than planets. The attitude-orbital coupled dynamics effect is related to the ratio between the spacecraft characteristic length and the orbital radius. It is thus much stronger around an asteroid than around a planet. This paper presents the effect of the attitude-orbital coupling on the orbital motion of a spacecraft around an asteroid. It also includes the effect of the solar radiation pressure in the context of the attitude-orbital coupled dynamics. [View Full Paper]

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EFFECTS OF SUBORBITAL TRAJECTORY DYNAMICS ON THE PHYSIOLOGY OF TOURISTS

Yi-Wei (Eva) Chang*[*] and Jeng-Shing (Rock) Chern[†]

The major purposes of this paper are to investigate the possible effects of trajectory dynamics of the reusable suborbital launch vehicle (RSLV) on the physiological conditions of tourists and to discuss the requirements of screening and training them before participating in suborbital space tourism (SST). Currently, there are three major RSLVs developed for suborbital scientific research and SST: Virgin Galactic's SpaceShipTwo (SS2), XCOR's Lynx and Blue Origin's New Shepard. Of these, SS2 and Lynx are of the horizontal-takeoff-horizontal-landing (HTHL) type and New Shepard is of the vertical-takeoff-vertical-landing (VTVL) type. Therefore, the commercial operations of SST might be expected to take place within a few years in the future. However, no matter whether the RSLV belongs to HTHL or VTVL, a rocket engine is being used as the propulsion system. As such, the trajectory dynamics and characteristics are very different from aviation airplanes. The SST tourists will experience the flight phases of high-g acceleration and deceleration, weightlessness, high level noise and vibration. All of these factors affect their physiological conditions at different levels. Major disorders include anxiety, decompression sickness, sensory conflicts, space motion sickness, severe vertigo, vomiting, etc. The connections between SST trajectory characteristics and tourists' screening/training requirements will be studied and discussed. [View Full Paper]

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INFLUENCE OF THE EARTH ROTATION PARAMETERS ON THE ACCURACY OF PREDICTING THE MOTION OF SATELLITE GLONASS

Alexey G. Toporkov* and Vsevolod V. Koryanov*

With the development of the global navigation satellite systems, the highly accurate determination and prediction of the Earth orientation parameters (EOP) has become an urgent and at the same time very difficult task. In solving modern problems, such as astrometry, geophysics and navigation is very important fundamental problem of constructing the fundamental dynamic models of rotational-vibrational motion of the Earth, which are will adequate observa-tions and measurements of International Earth Rotation and Reference Systems Service (IERS). The obtained results allow us to estimate the influence of the Earth's rotation parameters on the accuracy of prediction position of the navigation spacecraft. [View Full Paper]

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ORBIT DETERMINATION FOR LUNAR FARSIDE PROBE BASED ON RELAY COMMUNICATION SATELLITE

Yadi Yang,* Yuhua Tang† and Dong Qiao‡

This paper studies autonomous Orbit Determination (OD) process to track a lunar farside probe via a relay communication satellite. The feasibility of the scheme is verified via observation analysis. Orbit determination accuracies and converging velocities calculated by different initial position and velocity errors, different noises and different halo orbits are compared. The extended Kalman filter is used to process the measurement data. According to error analysis, the accuracy of the real-time states of the lunar farside probe can be achieved on the order of tens of meters with position in quite a short period. The results also show that, for a lunar probe on a relatively high altitude orbit, the initial errors can largely affect the OD performance, while the noise and the size of the halo orbit have little or no influences on it. [View Full Paper]

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:
Michael Ovchinnikov, Russia
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IAA-AAS-DyCoSS3-099
AAS 17-873

FEEDBACK CONTROL OF THE SPACECRAFT WITH A SOLAR SAIL FOR INTERPLANETARY FLIGHTS

Irina Gorbunova* **and Olga Starinova†**

This work is devoted questions of the solar sail's control, which performs an in interplanetary flight. The mathematical model of the solar sail spacecraft's movement includes the equations of the heliocentric movement in classic Keplerian elements. We use locally-optimal control laws to produce the heliocentric trajectory of the solar sail. These relations allowed us to propose the structure of the feedback control to automate the process of finding solutions. Authors receive some parameters of the flight and design parameter of solar sail spacecraft. Thus authors obtained results for manipulation of the solar sail, allows obtaining required trajectory for interplanetary flights. [View Full Paper]

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ANALYSIS OF RENDEZVOUS MANEUVERS EXPLOITING IMPEDANCE CONTROL TECHNIQUE

Angelo Stolfi,[*] Marco Sabatini,[†] Paolo Gasbarri[‡] and Giovanni B. Palmerini[§]

The impedance control technique commands the chaser interface – usually represented by a robotic arm – to behave like a mass-spring-damper system, absorbing the impact energy of the target and therefore maintaining a continuous contact in the following phases. The paper describes a complete implementation of this technique to one- and two-arms configurations of the chaser, referring to medium-class satellite platforms. The analysis is carried on numerically, by an extremely effective co-simulation approach combining MSC Adams for the multibody dynamics and Matlab/Simulink for the control. Additionally, a possible experimental set-up suitable for this approach and original applications of the technique to in-orbit operations are introduced. [View Full Paper]

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EVALUATION OF IMPULSIVE MANEUVERS PERFORMED BY ACTIVE SPACE OBJECT

Vladimir M. Agapov,[*†] Andrey A. Baranov[*‡] and Maksim O. Karatunov[‡]

The subject of this paper is the problem of estimating the maneuver parameters performed by an active space object between two consequent observations spans. Analytical and numerical-analytical algorithms of estimating one-pulse and two-pulse maneuvers of short duration are proposed. Both coplanar and non-coplanar types of maneuvers are considered. The algorithm for estimating single-pulse maneuvers takes into account presence of significant errors in determining the initial and final orbits. The solution process has a geometric interpretation. Examples of calculation are presented for the series of maneuvers of the spacecraft in GEO. [View Full Paper]

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HIGH-PRECISION GUARANTEED VALIDITY ESTIMATION METHODS APPLICATION FOR INTEGRATED INERTIAL NAVIGATION SOLUTION OF ORBITAL VEHICLES

Victor D. Dishel,[*] Aleksandr I. Sapojnikov[†] and Aleksandr V. Malishev[‡]

Theoretical and practical navigation solution correction aspects are discussed. The feature of the correction problem is that there may be errors in augmentation sensors output. These errors are unpredictable by its structure, gradient and value. Their distribution function and duration is also unknown. Augmentation sensors measurements processing by so-called interval-dynamic technique is considered. The base of the technique is combination of dynamic filtration and interval estimation formation. Results of 17 powered ascent missions from Guiana Space Centre, e.g. all 14 currently inserted "Galileo" satellites are discussed. Fregat space tug with integrated INS and software based on proposed method onboard was used in these missions. The ascent accuracy is better by one-two orders as compared to analogue ascent missions carried out using GNC systems of another Russian and foreign manufacturers. [View Full Paper]

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NEIGHBORING OPTIMAL GUIDANCE AND ATTITUDE CONTROL FOR LUNAR ASCENT AND ORBIT INJECTION[*]

Mauro Pontani[†] and Fabio Celani[‡]

Future human or robotic missions to the Moon will require efficient ascent path and accurate orbit injection maneuvers, because the dynamical conditions at injection affect the subsequent phases of spaceflight. This research is focused on the original combination of two techniques applied to lunar ascent modules, i.e. (i) the recently-introduced variable-time-domain neighboring optimal guidance (VTD-NOG), and (ii) a constrained proportional-derivative (CPD) attitude control algorithm. VTD-NOG belongs to the class of feedback implicit guidance approaches, aimed at finding the corrective control actions capable of maintaining the spacecraft sufficiently close to the reference trajectory. CPD pursues the desired attitude using thrust vector control, while constraining the rate of the thrust deflection angle. The numerical results unequivocally demonstrate that the joint use of VTD-NOG and CPD represents an accurate and effective methodology for guidance and control of lunar ascent path and orbit injection. [View Full Paper]

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THE CHOICE OF NANOSATELLITE GROUP SEPARATION PROGRAM: PROVIDING THE REQUIRED INITIAL NANOSATELLITES MOTION BY PIGGYBACK LAUNCHING

Denis P. Avariaskin[*] and Igor V. Belokonov[†]

This paper proposes the method of selection of the nanosatellites separation program from an undirected space platform at the stage of a flight task formulation. The method is based on statistical researches and provides a predetermined character relative motion of nanosatellites. The method of choosing of nanosatellites separation parameters is based on the criterion of minimizing a maximum distance between nanosatellites and with the exception of the possibility of dangerous approach. The method considered by the example of nanosatellites group separation from the orbital stage of the carrier rocket "Soyuz".

[View Full Paper]

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WAYPOINT-BASED GENERALIZED ZEM/ZEV FEEDBACK GUIDANCE FOR PLANETARY LANDING VIA A REINFORCEMENT LEARNING APPROACH

Roberto Furfaro[*] and Richard Linares[†]

Precision landing on large planetary bodies is a critical technology for future human and robotic exploration of the solar system. Indeed, over the past decade, landing systems for robotic Mars missions have been developed with the specific goal of deploying robotic agents (e.g. rovers, landers) on the Martian surface. In this paper, we proposed a novel algorithm that can generate powered, closed-loop trajectories to enforce flight constraints (e.g. no crashing on slope surfaces) while ensuring precision landing. More specifically, we propose a waypoint-based ZEM/ZEV algorithm that employs a dynamic programming approach via Value Iteration to determine the best location of the waypoints for a set of constrained landing over large planetary bodies (e.g. Moon and Mars). Here, the Reinforcement Learning (RL) framework is employed to integrate ZEM/ZEV with a waypoint selection policy as function of the current state of the spacecraft during the powered descent phase (i.e. position and velocity). Here, a set of open-loop, constrained, fuel-efficient trajectories are numerically computed using pseudo-spectral methods. A set of states from the open-loop optimal trajectories are stored as candidate waypoints. The latter are employed by the ZEM/ZEV algorithm as intermediate targets to steer the spacecraft toward the final target point on the planetary surface. The problem is cast as a Markov Decision Process (MDP) and the resulting dynamics programming problem is solved via generalized policy evaluation to select the next best intermediate target point as function of the previous one. The behavior of the integrated guidance algorithm is evaluated in Mars powered landing scenarios that involve demanding requirements both in landing location and flight path. Both constraints satisfaction and fuel efficiency are analyzed to show the effectiveness of the proposed approach. [View Full Paper]

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TO THE HIGH INCLINED ORBIT FORMATION WITH USE OF GRAVITY ASSISTS

Alexey Grushevskii,[*] Yury F. Golubev,[†] Victor Koryanov,[‡] Andrey Tuchin[§] and Denis Tuchin[**]

Effective space exploration is impossible without using gravity-assist maneuvers (GAMs). Their application relaxes the constraints imposed on the space mission scenarios by the characteristic velocity budgets being realized at the current stage of development of space technology. A significant change in the inclinations of operational spacecraft (SC) orbits in flight aimed at studying the inner heliosphere from out of ecliptic positions (the ESA "Solar Orbiter" mission, the Russian "Interheliozond" project, *etc.*) is needed to accomplish some prospective space missions. Low-cost tours for the high inclined orbit formation in the Solar system with use of gravitational maneuvers near its planets (Earth and Venus) with the full ephemeris using are considered. Limited dynamic opportunities of flybys use require multiple passes near them. Relevance of regular creation of optimum scenarios — sequences of cranking passing of celestial bodies and solution of conditions of their execution is obvious. The technology for synthesizing such scenarios is complicated by the necessity of their 3D design with allowance made for precise ephemeris models. This work is devoted to the description of beam's conditions for their creation of such chains. [View Full Paper]

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LOW THRUST TRAJECTORY OPTIMIZATION USING COVARIANCE MATRIX ADAPTATION EVOLUTION STRATEGY

Mikhail S. Konstantinov* and Min Thein†

Low thrust trajectory optimization problem is formulated by use of maximum principle. The trajectory optimization problem is reduced to the sum of squares of boundary conditions' residual and the required fuel with some weighting factor. In this case, the minimizing criterion is an additive function of the accuracy of satisfying the necessary optimality conditions for the maximum principle and the efficiency index of the transport operation in question. The weighting factor is considered as a parameter of continuation in the iteration process of solving the optimization problem and its final value is zero. This formulation helps to find the solution for the boundary value problem in the vicinity of the minimum fuel requirement using the method of evolutionary strategy with the covariance matrix adaptation. This method has shown high effectiveness for the analyzed interplanetary flights. Numerical results are presented. The problem of optimization of the trajectory of the spacecraft with electric propulsion to Mars with the optimization of its main design parameters is considered. Ten types of extremals are found and analyzed in the optimization of the direct flight to Jupiter for the spacecraft with electric propulsion.

[View Full Paper]

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METHODS OF SELECTING GUIDANCE LAWS TRANSFER VEHICLE WITH ELECTRIC PROPULSION SYSTEM DURING THE FLIGHT INTO GEOSTATIONARY ORBIT

Vadim Salmin* and Alexey Chetverikov†

Multicriteria optimization problem is formulated flight orbital transfer vehicle with electric propulsion system into location point of the geostationary orbit and offers its solution based on the principle of expanding the set of admissible states and departments. A method for solving the dynamic optimization problem of flight in geostationary orbit. As part of the methodology selects the nominal trajectory and guidance programs and their subsequent correction in the area long-range guidance based on the algorithm specification values of thrust. At the final stage of flight selects the terminal guidance algorithms to deduce the payload into location point of the geostationary orbit. [View Full Paper]

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FORECAST OF A COSMONAUT'S PERFORMANCE ON THE MARTIAN SURFACE AFTER A LONG-DURATION SPACE FLIGHT

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Yury V. Lonchakov[‡] and Maxim M. Kharlamov[§]

The paper gives the primary results of experimental studies performed at the Gagarin R&T CTC for the benefit of manned missions into deep space and carrying out works on Mars' surface by crew members just after completion a long-duration space flight. These experimental studies allow creating scientific and technical groundwork for efficient activity of crews of future manned space complexes under lunar missions programs, interplanetary transit flights and exploration of the solar system's planets. [View Full Paper]

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL BASED ON APPLICATION OF RESONANT TUNNELING DIODES IN NONLINEAR RADIO SIGNAL CONVERTERS

Mstislav O. Makeev,[*] Sergey A. Meshkov,[†]
Vladimir Yu. Sinyakin[‡] and Yury N. Razoumny[§]

The prospects of application of resonant tunneling diodes (RTD) based on nanoscale AlAs/GaAs heterostructures in non-linear radio signal converters of spacecraft guidance, navigation and control systems are demonstrated. A diagnostic model of the RTD has been developed. It makes it possible to obtain the kinetics of RTD current-voltage characteristics and the indices of non-linear converters of SHF radio signals under the influence of destabilizing factors during operation. The experimental data of the RTD current-voltage characteristic kinetics under the influence of destabilizing factors are presented.
[View Full Paper]

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MISSION DESIGN AND OPTIMIZATION

Session Chairs:
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Roberto Furfaro, U.S.A.
Tetsuo Yasaka, Japan
Antonio Bertachini Prado, Brazil

IAA-AAS-DyCoSS3-033
AAS 17-885

PARETO-OPTIMAL LOW-THRUST LUNAR TRANSFERS WITH RESONANT ENCOUNTERS

Maksim Shirobokov,[*] Sergey Trofimov[*] and Mikhail Ovchinnikov[†]

In this research, we construct low-thrust transfers to the Moon exploiting a series of resonant encounters. The initial orbit is either a low-Earth parking orbit or the geostationary transfer orbit. The transfer consists of the three stages: spiraling outwards to escape the radiation belts, fuel-optimal orbit raising, and a series of resonant encounters with the Moon that ends on a stable manifold of a halo orbit around the Earth-Moon L1. Varying the time of flight at the second stage, we get a Pareto front for different sets of input parameters (the initial orbit, the date and time of launch). [View Full Paper]

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INDIRECT OPTIMAL CONTROL FOR MINIMUM-FUEL LOW-THRUST EARTH-MOON TRANSFER

Daniel Pérez-Palau[*] and Richard Epenoy[*]

The aim of this work is to compute minimum-fuel low-thrust Earth-Moon transfers in the Sun-Earth-Moon Bicircular Restricted Four-Body Problem. First, the numerical difficulties related to the solution of this problem by means of indirect shooting methods will be detailed. To overcome these difficulties, a new robust indirect approach based on the use of a derivative-free algorithm will be presented. Numerical results will be provided demonstrating the efficiency of the developed method. Different families of medium-duration trajectories will be presented. Finally, long-duration low-energy trajectories exploiting manifolds defined in the two underlying Sun-Earth and Earth-Moon systems will be shown. [View Full Paper]

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OPTIMIZATION OF FLYBY SCHEMES IN THE FRAMEWORK OF ADR MISSION IN LEO

Andrey A. Baranov* and Dmitriy A. Grishko†

The paper focuses on the flyby issue involving large-size space debris (LSSD) objects in low Earth orbits. The data on overall sizes of the known upper-stages and last stages of launch-vehicles make it possible to emphasize five compact groups of such objects from the satellite catalogue in 600-2000 km altitude interval. Distinctive features of changes in mutual distribution of orbital planes of LSSD within a group are shown on the RAAN deviations' evolution portrait. In case of the first three groups (inclinations 71°, 74° and 81°), the lines describing the relative orientation of orbital planes are quasi-parallel. Such configuration allows easy identification of the flyby order within a group, and calculation of the mission duration and the required total ΔV. In case of the 4th and the 5th groups (inclinations 83° and 97-100°) the RAAN deviations' evolution portrait represents a conjunction of lines chaotically intersecting. The article compares two world-wide known schemes applicable to LSSD objects' de-orbiting. [View Full Paper]

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OVERVIEW OF MINI-MAGNETOSPEHERIC PLASMA PROPULSION FOR INTERPLANETARY TRAVEL

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Winglee and Funaki concept of MiniMagnetospheric Plasma Propulsion is reviewed and an appropriate M2P2 propelled spacecraft configuration is considered. A baseline study is carried out for practical applications and interplanetary trajectory parametric study. The orbital dynamics equation of motion for MagSail is elaborated and parametric studies are performed to explore probable interplanetary trajectories. The results of the analysis together with circle-to-circle planetary transfer such as Venus and Mars are elaborated for insight and comparative purposes. [View Full Paper]

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OPTIONS FOR STAGING ORBIT OF LUNAR ORBITAL STATION

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This paper focused on the options for staging orbit of lunar orbital station. Considering the reliability and safety of the mission, LLO is focused on through this paper. Both LOI and descent impulse are analyzed for different altitude. It is found that the lower the orbit, the less delta velocity for the total mission. The lunar accessibility is also researched on, from which the launch window for CSS is acquired and a rough range of RAAN is obtained. The lifetime and the maintenance cost are studied based on the analytical long period variation of eccentricity and the lunar gravity model. Combined all these factors, a 200km polar orbit is chosen as the mission orbit for LOS, which can support the global access to lunar surface or a lunar outpost mission. [View Full Paper]

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LOW THRUST TRANSFERS TO SPACE DEBRIS OBJECT NEIGHBORHOOD

Aleksey A. Budyansky[*] and Andrey A. Baranov[†]

The problem of spacecraft transferring to the vicinity of space debris object in close low-eccentricity non-coplanar orbits is considered. The transfer period is divided into two intervals. Each interval can contain up to several dozens of revolutions. It is assumed that the total duration of intervals is sufficient for correction deviations of all orbital elements including along-the-track deviation. Numerical-analytical algorithm for solving the rendezvous problem is offered, that allows determining the parameters of dozens of linked maneuvers and taking into account all the perturbations acting on the spacecraft (the influence of the atmosphere, the non-centrality of the gravitational field, etc.). The core of the algorithm is the analytical solution of impulse transfer (in five-dimensional space of deviations) between close low-eccentricity orbits. A distinguishing feature of proposed method is the using of simultaneous correction of all orbit elements, which allows obtaining close-to-optimal solutions for a wide range of deviations, while an analytical core allows to simplify and speed up solution search processes and to achieve high reliability of the proposed algorithm. This allows use the developed algorithm on the board of the debris collector spacecraft. The example of the solution of the problem is given.

[View Full Paper]

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TRADE SPACE VISUALIZATION APPLIED TO SPACE FLIGHT ENGINEERING DESIGN

David B. Spencer[*]

Spaceflight engineering design problems often contain correlations and trade-offs that may or may not be obvious or well-understood. As design problem complexity increases, decision makers find it more and more difficult to grasp these trade-offs effectively. The rapid growth of computing power now allows the simulation of millions of design alternatives. Understanding the trade-offs associated with these alternatives has never been more important. Trade space visualization tools are being developed to aid decision makers by allowing them to effectively explore a design space and identify the underlying trade-offs and nuances to a specific problem. These tools provide enormous potential in evaluating complex dynamical systems in spaceflight, among others.

This work reviews the work done at the Pennsylvania State University using the Applied Research Lab Trade Space Visualizer (ATSV) to various complex spacecraft engineering problems. Examples presented include optimal impulsive and continuous-thrust orbit transfers, interplanetary trajectory design, and spacecraft design. [View Full Paper]

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OPTIMAL INTERPLANETARY SPACECRAFT FLIGHTS DESIGN WITH MANY-REVOLUTION BRAKING MANEUVER BY A LOW THRUST JET ENGINE

Alexander S. Samokhin,* Marina A. Samokhina,† Maxim P. Zapletin‡ and Ilia S. Grigoriev§

The optimal control problem of the spacecraft (SC) interplanetary transfer from the Earth to Mars is considered. The orbits of the Earth and Mars are necessary to be circular and noncoplanar. The SC starts from the artificial Earth satellite circular orbit (AESCO) and finishes at the artificial Mars satellite circular orbit (AMSCO). The SC position on an initial AESCO at the starting point and position on an AMSCO at the finish are optimized. Accelaration of the SC near the Earth and braking near Mars, that are carried out by jet engines of big thrust, are approximated by pulse excitations. On the rest of the trajectory the control of the SC is realized by a low thrust jet engine vector. In connection with the taking into account the loss of accuracy effect, the inertial heliocentric and the noninertial rotating mars- and geocentric reference frames are used at the solution creation. Total flight time is minimized. The considered problem is formalized as a variable structure dynamic system optimal control problem. On the basis of the Pontryagins maximum principle its solving is reduced to the 42nd order boundary value problem solving. The boundary value problem is solved numerically by a shooting method with selection of 13 parameters. The vector function root is found with the use of Newton's method with Isaev-Sonin's modification and Fedorenko's normalization in the convergence conditions. The Cauchy problems of shooting method are solved numerically by the explicit 8th order Runge-Kutta's method based on Dormand-Prince's 8(7) calculating formula with the automatic step choice. Main result: the original problem has been solved. Pontryagin's extremals are defined out as a boundary value problem solution result. The analysis depending on problem parameters is carried out. Various AMSCO were considered during calculating. Particularly we succeed constructed Pontryagin's extremals in problems of transition to AMSCO which are close approximates Phobos and Deimos orbits without pulse influences at the finish moment. The SC performs a sixty six and a nineteen many-revolution brakings near Mars respectively at these constructed trajectories on the final part of flight. The parameters continuation of the planar case of problem solution is used to construct trajectories in the major case. Using of high and low thrust propulsion in combination for space missions allows increase the useful weight and makes the project cheaper, that is actual now. Expeditions to Mars and its natural satellites can help to provide solution of a wide range of scientific physics problems of the Solar system. [View Full Paper]

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LUNISAT: A MICROSATELLITE MISSION TO THE MOON*

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In recent years, microsatellites have been designed, constructed, and operated by a considerable number of subjects, either Universities, space agencies, or private ventures. This research presents the overall mission analysis for Lunisat, a next-generation microsatellite that is intended to orbit the Moon. The Lunisat mission is assumed to be composed of two main phases: (a) transfer trajectory from a low Earth orbit (LEO) to a low Moon orbit (LMO), and (b) release of nanosatellites around the Moon. As a first step, the optimal two-impulse transfer is obtained, under some simplifying assumption. Then, the transfer trajectory is investigated using very accurate dynamical modeling, and a first analysis on continuous-thrust transfers is addressed. The second phase of the Lunisat mission includes the release of two or more nanosatellites, and is affected by the masconian character of the Moon gravitational field. This work investigates the orbit evolution as a function of the dynamical conditions at release, adopting a relatively long propagation time and employing a gravitational model that includes the most relevant terms, as well as third body effects due to Earth and Sun. [View Full Paper]

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OPTIMIZATION OF THE LUNAR TRANS-EARTH INJECTION WITH THE MULTI-IMPULSE TRANSFER

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The problem of the return from the Moon's artificial satellite orbit to the Earth is considered. The main goal is to develop and to implement the algorithm for the lunar trans-Earth injection's trajectory computation using three impulse maneuvers. The advantage of using the trajectory of multi-impulse transfer is that the total costs of the characteristic velocity in this case are less than the one-impulse transfer. Different schemes of the impulse maneuvers sequence are compared. The results of the numerical simulation for the three-body problem (the Earth, the Moon, the spacecraft) considering noncentral gravity models are presented. [View Full Paper]

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SIMULTANEOUS OPTIMIZATION OF THE LOW-THRUST TRAJECTORY AND THE MAIN DESIGN PARAMETERS OF THE SPACECRAFT

Viacheslav G. Petukhov,[*] Woo Sang Wook[†] and Mikhail S. Konstantinov[*]

The problem of the simultaneous optimization of the low-thrust trajectory of the spacecraft, the main design parameters of its electric propulsion system and power supply system is considered. The optimization criterion is the spacecraft useful mass. The thrust vector orientation program, the thrust switch on/off moments, and trajectory parameters (the launch date, the departure hyperbolic excess velocity direction and value) are being optimized. Alongside with the control program and the trajectory parameters, the main parameters of the electric propulsion system (maximum power consumption, specific impulse) and the power supply system (initial electric power at the heliocentric distance of 1 AU) are being optimized. The necessary optimality conditions, the main methodical ideas, and the numerical examples of optimal low-thrust Earth-Mars missions are presented.

[View Full Paper]

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STABILITY OF A MOVING CONTROL OF A SERVICE SC AND A SPACE DEBRIS OBJECT AT IMPACT ON IT BY AN ION BEAM

V. A. Obukhov,[*] A. I. Pokryshkin,[*] G. A. Popov[*] and V. V. Svotina[*]

The problem of service spacecraft (SSC) control algorithms was studied as applied to the space debris removal from the protected GEO region by the Ion Shepherd method. That study was made by numerical modeling for the dynamics of motion of a cluster consisting of two objects, one of which being an uncooperative object of space debris and another one - SSC with the ion injector on board. The motion of the latter is controlled by an electric propulsion (EP) with controllable thrust vector. Conditions are defined, under which the control by the proposed algorithms is stable. [View Full Paper]

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SYSTEMS ENGINEERING DESIGN AND OPTIMIZATION OF AN ACTIVE DEBRIS REMOVAL MISSION OF A SPENT ROCKET BODY USING PIGGYBACK AUTONOMOUS MODULE

Valery Trushlyakov[*] and Vadim Yudintsev[†]

This paper presents a preliminary analysis of the piggyback active debris removal mission using an upper stage after completing its main mission as the space tug for debris removal. To solve the specific tasks related to the active debris removal the tethered autonomous module is installed on the upper stage with a capture device and necessary equipment for autonomous navigation and motion control. Several phases of the mission are analyzed including the proximity phase before the separation of the autonomous module, catching phase, post-capture de-tumbling and tether stabilization phase. The results obtained can be used to formulate the requirements for the autonomous docking module design and parameters of the demonstration experiment. [View Full Paper]

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ALGORITHM OF THE B-PLANE DELIVERY ERROR ESTIMATION FOR THE MISSION TO VENUS

Alexander Gammal[*†]

Payload delivery error is required to be estimated for the interplanetary mission design. Such estimations can be used not only at mission development stage, but also at mission execution stage. An algorithm developed to solve this problem is presented. It’s supposed that nominal trajectory, correction maneuvers schedule and initial injection error covariance matrix are known. Maneuvers are considered impulsive. Trajectory deviations are represented as scattering set of position and velocity deviations from the nominal trajectory at some initial time. The calculations were made for the mission to Venus known as “Venera-D”. The results obtained by usage of the algorithm are presented.

[View Full Paper]

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MISSION DESIGN OF ADAPTING MARS ENTRY, DESCENT AND LANDING SYSTEM FOR EARTH: RITD-PROJECT

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The task motion of the spacecraft in the atmosphere is a complex and very important to carry out the planned mission. For the design of such a mission it has developed a special technology for the descent of the spacecraft in the atmosphere of the planet. This technology is based on the concept of using inflatable braking devices and was originally developed for landing in conditions of Mars. Idea of this project - to assess the possibility and the advantage this technology for use in a descent into the Earth's atmosphere to deliver payloads of small size with low-Earth orbits. [View Full Paper]

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METHOD OF ENERGY ESTIMATION OF INTERORBITAL TRANSFERS FOR LEO SPACECRAFT ON-ORBIT SERVICING

Andrey A. Baranov,* Vladimir Yu. Razoumny,†
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The problem of planning the circumnavigation of space objects requiring servicing is considered. It is assumed that system of base stations for servicing the given array of the satellites on different LEO orbits has been deployed. For a fixed time it is needed to flyby each satellite which requires servicing. The servicing is conducted using the detachable orbital modules (OM) from the base stations (BS). Basing on the longitude of ascending node deviation portrait for all serviceable satellites and base stations it is defined which OM should transfer to the vicinity of which satellite in order to have the lowest Delta-V budget. [View Full Paper]

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METHOD OF OPTIMAL TRAJECTORIES DESIGN FOR A SPACECRAFT WITH A JET ENGINE OF A LARGE LIMITED THRUST IN PROBLEMS WITH THE PHASING CONDITION

Marina A. Samokhina,[*] Alexander S. Samokhin,[†] Maxim P. Zapletin[‡] and Ilia S. Grigoriev[§]

The optimization of the spacecraft (SC) interplanetary space flight trajectory is considered. Rigid conditions of phasing are supposed on one of the trajectory bound point. The SC docks to/undocks from the existing station or lands on/flies up from the natural satellite of the planet. On another end hit the point type rendezvous condition is considered. The SC and the station/the planet natural satellite are relied to be non-attracting material points. The control of the SC is realized by a large limited jet engine thrust. The start, the finish, the moments of inclusion and switching off of the SC jet engine thrust are optimized. Weight losses are minimized. The problem is formalized as an optimal control problem and decides on the basis of the Pontryagin's maximum principle. The boundary value problem is solved numerically with the use of shooting method, Newton's method and the parameters continuation method. Transversality conditions of a maximum principle are effective for the time optimization on the trajectory end with hit the point condition. And for time optimization on the bound point with a phasing condition – the external optimization with the use of a combination of gradient methods and a method of continuation of the decision on parameter is made. One of the main difficulties in solving of such problems is constructing good initial parameter values approximation. As example, technique of creation extremals in the problem is showed on the SC returning with samples of soil from the Mars satellite Phobos to the Earth optimization, with taking into account ephemerides. The original problem is multiextremal, a launch window to the Earth from Mars opens each two years. Besides, for each round of Phobos around Mars exists a local optimum trajectory. Therefore, in the beginning of solution global optimization is made: the SC flight is approximated with series of close Lambert's problems. Then the problem is solved in pulse statement on the basis of the Lagrange principle with consideration of the Sun, and Mars attraction on each part of the trajectory. [View Full Paper]

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OPTIMAL DIRECTION OF THE HYPERBOLIC EXCESS VELOCITY VECTOR AT THE BOUNDARY POINTS OF THE HELIOCENTRIC FLIGHT

Mikhail S. Konstantinov*

It is often asserted that in the optimality conditions the hyperbolic excess velocity vector and the primer vector (the adjoint vector to the vector of the heliocentric velocity of the spacecraft) at the start of the interplanetary flight are collinear. In the analysis of optimal interplanetary trajectories of the spacecraft with electric propulsion, several studies have shown that this statement is not always true. It is shown that, if the magnitude of the hyperbolic excess velocity vector exceeds a certain critical value, the optimum direction of the hyperbolic excess velocity vector must be anti-collinear to the primer vector. It was noted that Lagrange multiplier (the coefficient of proportionality between the hyperbolic excess velocity vector and the primer vector) should be used to write optimality conditions in the correct form. The sign of Lagrange multiplier will characterize whether the hyperbolic excess velocity vector must be collinear or anti-collinear to the primer vector. The main purpose of this study is the analysis of the nature of the dependence of Lagrange multiplier on the hyperbolic excess velocity value. It is shown that the dependences of the optimal characteristics of the flight path are not smooth functions of the magnitude of the hyperbolic excess from the Earth. Such character of the dependences should be taken into account while developing methods for optimizing interplanetary trajectories of the spacecraft with electric propulsion. [View Full Paper]

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MANAGEMENT OF THE APPLICATION OF THE SPACE GEOINFORMATION SYSTEM IN THE INTERESTS OF ENSURING THE ENVIRONMENTAL SAFETY OF THE REGION

Vyacheslav G. Burlov[*] and Nikolay N. Popov[†]

The system of space monitoring (SM) is of great importance, as a means of ensuring environmental safety. This system is based on remote sensing. The structure of SM is a distributed system. This system comprises independent data storage, system control, system of dynamic ratings and forecasting, control system, information system (IS) processing of monitoring data. As IS it is necessary to choose a geographic information system (GIS). IS monitoring refers to the problem-oriented system. These information systems include specialized databases models. All monitoring systems use sets of models, which allow to build complex enterprise models. The peculiarity of the SM is the need to coordinate support of this monitoring. Production Manager's decision is the impact on the object of monitoring. Results management and environmental data are received at the monitoring subsystem. Geoinformation system of monitoring forms a closed system. Integration of SM and GIS monitoring has led to the creation of geoinformation space monitor (GISM). The operation of the system GISM is designed to provide a guaranteed result. Basis – the decision of the decision makers (DM). Therefore, an independent scientific and practical interest is the adequate mathematical model of DM. The solution of the problem of synthesis of adequate mathematical model of the DM solution and the subject of this article.

[View Full Paper]

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THE EQUAL-COLLISION-PROBABILITY-SURFACE METHOD FOR SPACECRAFT COLLISION AVOIDANCE

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To improve the computational efficiency of spacecraft collision probability calculation, an Equal Collision Probability Surface (ECPS) method for the spacecraft collision avoidance problem is developed for the nonlinear relative motion in this paper. Firstly, the ECPS concept is established. Like the concept of isobaric surface, ECPS represents the surface consisting of equal collision probability points in the space around the debris. According to the effect of control uncertainty and navigation uncertainty, the ECPS of spacecraft is established. As the fastest change of the ECPS is along the ECPS's gradient, the direction of the collision avoidance maneuver along the gradient is optimal. To calculate the ECPS's gradient, a novel auxiliary function, which has equal gradient with the collision probability function, is proposed to achieve the gradient value. Compared with the traditional collision probability function, the proposed auxiliary function does not need solving the transcendental function after the approximately treatment, so that the computing burdening can be greatly decreased while maintaining the accuracy. With the gradient, the control force can be generated and the spacecraft can achieve collision avoidance effectively. Through comparisons in the numerical simulations, the novel ECPS method is validated to be more computationally effective than the traditional methods with almost the same gradient accuracy. [View Full Paper]

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OPTIMAL CONTROL IN SPACE FLIGHT DYNAMICS

Session Chairs:
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ESTIMATION OF THE RADIATION HAZARD TO A SPACECRAFT PASSING THE VAN ALLEN BELTS IN A LOW THRUST TRANSFER

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A spacecraft transfer from a low Earth orbit to outside the Earth sphere of influence using solar electric propulsion is considered. The spacecraft crosses the Van Allen belts many times during the transfer, what can damage the onboard electronic equipment. A simple model of the belt is taken: the belt consists of two spherical parts with homogeneous radiation. The radiation accumulated during the spacecraft passage through the belts is estimated for various transfer orbits using the model. This estimate is done for various parking orbits and transfer times. [View Full Paper]

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DESIGN AND OPTIMIZATION OF A NONLINEAR LYAPUNOV-BASED ATTITUDE CONTROL LAW FOR RIGID SPACECRAFT

Mojtaba Niknezhad[*] and Franco Bernelli-Zazzera[†]

In this paper, a nonlinear Lyapunov-based attitude control law is proposed to perform on-orbit slewing maneuvers and stabilization for spacecraft. A new class of Lyapunov function candidate, which includes a quadratic term and a nonlinear kinematic term based on direction cosine matrix has been proposed. The structure of the Lyapunov function candidate allows for the design of a control algorithm, which includes a linear combination of three unit vectors multiplied by three scalar coefficient functions. The coefficient functions are explicitly present in the Lyapunov function description. The coefficient functions can be easily replaced by other families of Lebesgue integrable functions. In this paper a specific coefficient function based on a geometric feature is represented. The functions involve the use of three inertial spheroids, which have their 2nd focuses on the spacecraft center of gravity. The values of the coefficient functions are evaluated based on the distance of some specific points on these spheroids. Moreover, a nonlinear global optimization of the controller is done, which aims to reduce the settling time and total effort of the attitude maneuver. In particular, Particle Swarm Optimization method is used in order to minimize the objective function. The nonlinear optimization will evaluate the gains and also the optimum shape of the spheroids to be used in the Lyapunov function. The results of the numerical simulation for this control law have been compared with two conventional PD attitude controllers, and has shown a superior performance in terms of settling time and total effort for slew maneuvers. Furthermore, the sensitivity of the controller to uncertainties in inertia matrix and control input is evaluated, and compared to other controllers. [View Full Paper]

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ACCURATE MODELING AND HEURISTIC TRAJECTORY OPTIMIZATION OF MULTISTAGE LAUNCH VEHICLES[*]

Guido Palaia,[†] Marco Pallone,[*] Mauro Pontani[‡] and Paolo Teofilatto[§]

Multistage launch vehicles are commonly employed to place spacecraft in their operational orbits. Several characteristics, i.e. mass distribution and time variation, propulsion, and aerodynamics, affect the overall performance of the ascent vehicle of interest. Thus, it is apparent that accurate modeling is a central issue and an essential prerequisite for trajectory optimization. This research uses the Scout, a launch vehicle of reduced size used in the past, as the reference multistage rocket. Its ascending trajectory is assumed to be composed of five arcs: (i) first stage propulsion, (ii) second stage propulsion, (iii) third stage propulsion, (iv) coast arc (after release of the third stage), and (v) fourth stage propulsion. The Euler-Lagrange equations and the Pontryagin minimum principle, in conjunction with the Weierstrass-Erdmann corner conditions, are employed to express the thrust direction as a function of the adjoint variables conjugate to the dynamics equations. The use of these analytical conditions coming from the calculus of variations leads to obtaining the overall rocket dynamics as a function of a few parameters only, mainly represented by the unknown values of the initial costate components. Then, a heuristic algorithm, e.g. particle swarm, is used to determine the optimal parameter set. The path constraint related to the maximum dynamical pressure is taken into account. The numerical results unequivocally prove that the methodology at hand is rather effective and accurate, and definitely allows evaluating the performance attainable from multistage launch vehicles with accurate aerodynamics and propulsive modeling. [View Full Paper]

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INVERSE PROBLEMS IN THE METHOD FOR STOCHASTIC PERTURBATION OF SINGULAR MATRIX DECOMPOSITIONS FOR SPACECRAFT TRAJECTORY OPTIMIZATION ALGORITHMS

Vladimir Kulikov[*] and Valery Khranilov[†]

A stochastic version is offered for the analysis of the computational algorithm of linear algebra - the SVD decomposition - based on the singular value identification by the method for solving the first-kind Fredholm integral equation on restricted sampling. The scope of application shall be: control systems for space and aircrafts (putting of spacecrafts (SC) into preset orbits, navigation and descent mode testing), the analysis of multidimensional data arrays. The knowledge of the perturbation distribution laws and their influence on computational algorithms determine the optimality or problems in the trajectory calculation, the landing coordinate deviation. [View Full Paper]

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AIR-BREATHING RAMJET ELECTRIC PROPULSION THRUSTER FOR CONTROLLING LOW-ORBIT SPACECRAFT MOTION AND FOR COMPENSATING ITS AERODYNAMIC DRAG

G. A. Popov,[*] M. O. Suvorov,[†] S. A. Syrin[‡] and S. A. Khartov[§]

If remote sensing of the Earth satellites orbit's altitude is decreased down to 180-280 km, it increases significantly the efficiency of onboard equipment. For such spacecraft's active lifetime increasing its aerodynamic drag should be compensated by using propulsion system with eclectic thruster (EP). The problem is that for EP operation the solar array area should be increased and as a result the aerodynamic drag rises and it requires to increase propellant's mass for its compensation. The way is to decrease propellant mass by intaking it from the atmosphere around the spacecraft, i.e. to use the air-breathing ramjet electric propulsion thruster. [View Full Paper]

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VERIFICATION OF THE SECOND-ORDER OPTIMALITY CONDITIONS IN THE MODELING OF THE SC EXPEDITION WITH THE RETURNING TO THE EARTH BASED ON TWO LAMBERT'S PROBLEMS SOLVING

Alexander S. Samokhin[*] and Marina A. Samokhina[†]

The interplanetary spacecraft (SC) expedition from the Earth to Mars with a returning to the Earth optimization problem is considered. The attraction of the Sun only is taken into account. Two trajectories of interplanetary flights of this mission are approximated by Keplerian orbits and are obtained as solutions of Lambert's problems with the use of universal variable, Stumpff functions and Newton's method. The positions and the velocities of the Earth and Mars are calculated with the use of ephemerides DE424. The SC starts from the Earth for the period of 2020-2030 and stay at field near Mars at least for 30 days to carry out near-Mars scientific investigation. The total time of the expedition is limited to 1500 days. The characteristic velocity is minimized. The 64 local minima of this multiextremal problem are found numerically with the use of the gradient method and examined with the second-order optimality conditions with the use of Sylvesters criterion. Each Lambert's problem is given by two moments of time—moments of start and finish of the SC in this statement. So corresponding matrixes are 4x4. The subject of the article is actual in connection with the growing interest in the study of other planets of the Solar System and near-planetary spaces, and accordingly the planning of such missions. This study is the first part of the solving optimization problems in more complex statements—namely, a rough global optimization is performed to find potentially optimal time intervals for such missions with the verification of their optimality. The paper describes the method and gives certain results. [View Full Paper]

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METHOD OF TWO-PARAMETERS CONTROL OF SPACECRAFT DURING DESCENT IN THE MARS ATMOSPHERE

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An important task of a spacecraft control is to minimize the final speed of the device at the height of putting in operation the soft landing system. It should be noted that the complexity of decay in the Mars atmosphere is related to rarefaction. Therefore, limitations on overloads and temperatures should be taken into account when optimizing the trajectory of launching a spacecraft. These factors affect the appearance of the spacecraft and its mass. The paper presents the method of simultaneous control of a spacecraft using an attack angle and a roll angle using ricochet trajectories. With the help of this method, the problems of minimizing the final speed, reducing the maximum temperatures and overloads acting on the spacecraft during the movement in the aerodynamic braking area are solved. [View Full Paper]

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CONTROL SYNTHESIS BY NETWORK OPERATOR METHOD FOR SPACECRAFT DESCENT ON THE MOON

Askhat I. Diveev,[*†] Elena A. Sofronova[‡] and Dmitry A. Ryndin[§]

A control synthesis problem for spacecraft descent to the given domain near the Moon is considered. Mathematical model of the spacecraft, initial states, and terminal conditions are given. The goal is to synthesize the control so that the spacecraft could obtain the terminal state from the given domain of initial state in limited time. The synthesized control is a multidimentional function that describes dependence of control from the state coordinates. In this paper to solve the control synthesis problem we use a new numerical method of network operator. An example of spacecraft descent is given.

[View Full Paper]

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RAPID TRAJECTORY OPTIMIZATION FOR LUNAR SOFT LANDING WITH HAZARD AVOIDANCE

Cong Wang* and Zhengyu Song†

This paper presents a rapid trajectory optimization for fuel-optimal lunar soft landing in the presence of hazard avoidance. First, the basic lunar soft landing trajectory optimization with the dynamics model, boundary conditions and path constraints is formulated, and the original trajectory optimization problem is discretized into NLP problem. Subsequently, the adaptive pseudospectral method is selected to solve the original lunar soft landing trajectory optimization problem, and the location of collocation points could be located near the breakpoints. Depending on various terrain obstacles, barrier avoidance or re-select landing point are both discussed. Meanwhile, two scenarios, landing from pinpoint and landing from orbit, are also demonstrated. Considering the terrain barriers and updated landing point, the homotopy method is proposed to transcribe the trajectory optimization problem into a homotopy function, and generate the reasonable initial guess for the optimal problem. Simulation results indicate that the proposed homotopy-based trajectory optimization method has sufficient adaptability to handle complex and unpredictable lunar soft landing scenarios in improving the convergent performance, and plan a feasible trajectory on-board. Applying this method to HDA, the vehicle can rapidly obtain the optimal path based on real-time detected terrain information, and it may ultimately benefit the future autonomous lunar soft landing mission. [View Full Paper]

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ATTITUDE SENSORS AND ACTUATORS

Session Chairs:
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AAS 17-914

FUELLESS MEANS OF REACTION WHEELS DESATURATION

Yaroslav Mashtakov,[*] Mikhail Ovchinnikov[†] and Stepan Tkachev[‡]

In paper, we consider a spacecraft on highly elliptical orbit. Reaction wheels are used to maintain sun orientation but because of different external disturbances – such as gravitational and solar radiation pressure torques – they cumulate excessive angular momentum and after awhile they will not be able to produce the necessary control torque. Hence, it is necessary to desaturate them. In order to save propellant and expand active lifetime or payload mass of the satellite we suggest an algorithm of angular motion synthesis that utilizes solar radiation pressure and gravitational torques and allows us to desaturate reaction wheels. [View Full Paper]

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A MANIPULATOR ROBOT FOR FAST AND ACCURATE POSITIONING OF THE OBJECT

A. A. Vnykov* and Shabnom Mustary†

This article discusses the features of the spatial processes of fast and accurate positioning of points on the external surface of the object using the manipulation robot when executing the sequence of technical operations. Considered, pregenerating digital models of the external surfaces of the object. The quality of obtaining the coordinates of the points of an object's surface, determines the accuracy of positioning the surface of an object in the working zone. Simulation of positioning the moving points on the surface of the body in the working zone of a robotic system to capture the object is determined relative to a fixed point of another object, with respect to which positioning is to perform technical operation. When it is not sufficiently accurate and fast positioning then it is required a new surface model of an object and positioning the technical points on the surface. The simulation in MATLAB making a conclusion about the possibility of application of fuzzy controller for fast and accurate correction values of a small deviations from the coordinates of selected technical points of the surface of an object in the given vectors in its orientation and approach to the fixed point of another object. [View Full Paper]

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DYNAMICS AND CONTROL CHALLENGES FOR IMAGING SATELLITES

Brij N. Agrawal[*] and Jae Jun Kim[†]

Imaging satellites have several challenges in dynamics and control to meet high performance requirements. As an example, Hubble Space Telescope pointing requirements are of 0.012 arc-sec and jitter requirements not to exceed 0.007 arc-sec. These satellites require fast slew maneuver with minimum slew time. Flexibility/control interaction becomes critical for these satellites. These satellites require fine mirror surfaces for diffraction limited performance. For visible images, the surface mirror accuracy requirements are a minimum of 30 nm. In order to meet these performance requirements, advance dynamics and control techniques and actuators and sensors are required. Meeting these requirements becomes even more challenging for future imaging satellites as the diameter of primary mirrors increases, resulting in deployable mirrors. This paper provides an overview of advanced dynamics and control techniques for jitter control, flexibility/control interactions, slew maneuvers, and reflector active surface control.

[View Full Paper]

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MICROSATELLITE ATTITUDE MOTION DETERMINATION USING MEASUREMENTS OF ELECTROMOTIVE FORCE INDUCTED IN MAGNETIC TORQUERS

Danil Ivanov[*] and Michael Ovchinnikov[†]

The paper proposes an algorithm of three-axis attitude determination using measurements of electromotive force (EMF) induced in magnetic torquers. The extended Kalman filter is applied. The paper studies the accuracy of the developed algorithm, its dependence on angular motion of the satellite and measurement noise. [View Full Paper]

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RADIO-FREQUENCY ION THRUSTER APPLICATION FOR THE LOW-ORBIT SMALL SC MOTION CONTROL

R. V. Akhmetzhanov,[*] A. V. Bogatyy,[†] V. G. Petukhov,[‡] G. A. Popov[§] and S. A. Khartov[**]

To provide long-term operation of spacecraft (SC) in low-orbit, it is necessary to correct its motion periodically in order to compensate for the SC aerodynamic drag. Duration of such SC orbital life is limited by the store of propellant of the corrective propulsion system and its lifetime. Therefore, application of electric propulsion (EP) with high specific impulse and long lifetime provides longer operating life comparing to the traditional application of liquid-propellant engines for such tasks. Ion thrusters with electrodeless inductive radio-frequency discharge with relatively low power (from 300 to 1000 W) developed by RIAME MAI have performance that make them competitive in the market. [View Full Paper]

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OPTIMAL SYNTHESIS OF SATELLITE ATTITUDE DETERMINATION AND CONTROL SYSTEM'S PARAMETERS

Meirbek Moldabekov,[*] Daulet Akhmedov,[†] Suleimen Yelubayev,[†] Kuanysh Alipbayev[†] and Anna Sukhenko[†]

This article discusses the problem of ensuring the quality of transient process of satellite attitude determination and control system. Optimal synthesis control is used for ensuring the required quality of transient process with regard to space systems in world practice. In this paper we consider the approach to optimal synthesis of satellite attitude determination and control system based on the optimal location of the poles of the closed-loop control system. The problem of control of slew from current angular position to desired in minimum time is solved using given approach. Analysis of the numerical solution of this problem has shown the effectiveness of given approach. [View Full Paper]

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SPACE STRUCTURES AND TETHERS

Session Chairs:
Filippo Graziani, Italy
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DYNAMICS AND CONTROL OF TETHER-ASSISTED RENDEZVOUS IN LEO

Vladimir S. Aslanov[*] and Ruslan S. Pikalov[†]

This study focuses on the dynamics of a rendezvous of a tug and a large space debris connected by a viscoelastic tether. It is assumed that the constant thrust acts on the space tug and a control is realized by changing the length of the tether. The goal is to find the control law that provides a soft docking of two bodies on an orbit. Three-body system with an additional damping device is also considered. This damping device allows to eliminate oscillations during the final docking phase. Analysis of the consistency of the proposed law with the requirements of safe rendezvous of the bodies is carried out. The obtained results can be applied as applications for the tasks of implement rendezvous of two bodies using the tether. [View Full Paper]

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SPACE ELEVATOR: A REALISTIC MODEL AND ITS STATIC AND DYNAMIC BEHAVIORS

Tetsuo Yasaka*

Theoretical and experimental endeavors have been reported toward realization of Space Elevator. However, neither is far from final solutions and their assumptions are not coherent. A space elevator configuration is constructed considering ongoing experiments of space climbers that go up a few thousands meters from ground. Adopting a realistic assumption reflecting the climber experiments on the lower portion of the elevator, configuration of higher portion up to 100,000 km can be determined by considering static and dynamic behaviors of the tether synchronized with the earth revolution in the equatorial plane. Deployment simulation is conducted based on this model. First all elements are put on an orbit a bit higher than the geosynchronous altitude and then elements are gradually deployed one by one vertically both up and down until the lower end reaches the surface of the earth. Based on the model, a realistic milestone to the establishment of space elevator system will be proposed. [View Full Paper]

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DEPLOYMENT AND STABILIZATION OF AN AERODYNAMIC SPACE TETHER SYSTEM

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The aerodynamic space tether system consists of two bodies – a spacecraft plus a stabilizer – which are connected by a tether. The deployment of the system is mainly effected by aerodynamic forces. In the mathematical modelling, the tether is represented by a number of material points with elastic connections. The aerodynamic resistance of the tether and its mass characteristics are both taken into consideration in the calculation. Different methods of deployment and system dynamics are investigated. These investigations enabled the comparison of the motion of systems comprising a light-weight and relatively short tether with those with a longer tether. [View Full Paper]

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METHOD OF TETHERED SYSTEM CONTROL FOR DEORBITING OBJECTS USING EARTH'S ATMOSPHERE

Yury N. Razoumny,[*] Sergei A. Kupreev[†] and Arun K. Misra[‡]

A space tethered system used as an atmospheric braking device for deorbiting small satellites from low orbits is considered. A simplified mathematical model of a small space tethered system that takes into account aerodynamic drag of the upper layers of the atmosphere and tether mass has been developed. A mathematical tool of dynamic systems qualitative theory and bifurcation theory is used for the given model analysis. The feasible modes of tethered system motion during descent in the upper layers of the atmosphere are defined. The most rational mode of tethered system is singled out relying on the stated efficiency factors. Based on CubeSat-type spacecraft, the application of different tethered system design options have been reviewed. Tethered systems of approximately 2 km long are proved to be efficient for deorbiting small satellites from low nearcircular orbits.
[View Full Paper]

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MODELING AND ANALYSIS OF DEPLOYMENT DYNAMICS OF A DISTRIBUTED ORBITAL TETHER SYSTEM WITH AN ATMOSPHERIC SOUNDER

Zhe Dong,* Y. M. Zabolotnov† and Changqing Wang‡

This paper analyzes the dynamics of an orbital tether system. The orbital tether system consists of a spacecraft and an atmospheric sounder that are connected by a tether. We take into account the effect of the aerodynamic force acting on all elements of the system for developing a nominal deployment program of the tether system. A linear controller with feedback in terms of tether length and deployment rate for compensating the errors arising from the impact of small perturbations is used for implementing the proposed nominal deployment program. Taking into account the effect of aerodynamic force can significantly decrease the errors of bringing the system to a predetermined vertical state compared with the known deployment programs. The numerical simulations of the deployment process demonstrate the effectiveness of the proposed nominal deployment program. [View Full Paper]

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SATELLITE CONSTELLATIONS AND FORMATION FLYING

Session Chairs:
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IAA-AAS-DyCoSS3-126
AAS 17-925

GROUND SPACECRAFT CONTROL FACILITIES DISTRIBUTION BY METHOD OF SUCCESSIVE ELIMINATION OF CONFLICTING SITUATIONS

Maksim M. Matyushin,[*] Vladimir M. Ovechko,[†] Vladimir M. Polivnikov,[‡] Yury N. Razoumny,[§] Oleg P. Skorobogatov[**] and Daria D. Tyurina[††]

One of the possible solution for the task of SC constellations ground control facilities distribution is analyzed; namely temporal resource distribution of test and control systems for communication sessions with SCs. Planning algorithm of the communication sessions is described in this paper. The algorithm is employed in software. Data example is described; the data is based on the feedback from experiment with developed software.

[View Full Paper]

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A FORCE-CONTROLLED ROBOTIC SYSTEM FOR A SERVICING SPACECRAFT: CONCEPT DESIGN AND DEVELOPMENT TESTING

Igor Shardyko,[*] Igor Dalyaev[†] and Victor Titov[‡]

In order to provide prolonged lifetime and enhance safety of unmanned spacecraft, especially on high orbits including geostationary ones (GEO), application of service space assets is considered. A concept of such an asset comprises a spacecraft (servicer) equipped with manipulation system capable of on-orbit servicing tasks, including refueling, equipment replacement (upgrade), orbit correction (repositioning), repair, contact inspection, etc. The execution of these tasks can be greatly simplified with introducing force-torque technology.

This paper starts with the analysis of actual failures lastly sustained by commercial satellites and reveals potential benefits of servicing spacecraft employment. Robotic system application is justified and a set of robotic tasks is determined. To meet the requirements of executing these tasks, a general concept of manipulation system is proposed. Next, the tasks are thoroughly considered to define their stages and also the criteria for advancing to the next stage, which leads to developing relevant control algorithms implementing the force-torque technology. Impedance and hybrid control laws are mostly considered and for each of them customization capabilities are specified. A small-scale experimental model has been designed to verify the algorithms by conducting the development testing on the ground validation facility. Particular attention is paid to the variety of performed tests including an imitation of the peg-n-hole task, contact inspection and also handling the contact with an unexpected obstacle. The conclusion comprises the outline of the results and the experiments to be conducted in the future. [View Full Paper]

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OPTIMAL FORMATION AND REPLENISHMENT OF LUNAR SATELLITE CONSTELLATIONS

Andrey A. Baranov,* Dmitriy A. Grishko† and Borislav O. Vasilkov‡

The paper focuses on the problem of formation and replenishment of Lunar satellite constellations. It is supposed that the orbital inclination was formed during the transfer to the orbit around the Moon. The arrangement of satellites according to their required positions is to be carried out using the special drift orbit. The precession velocity and revolution period of this orbit differ from the parameters of future operational orbits. The usage of a drift orbit allows to solve two tasks: it is possible to form the configuration of satellites in one orbital plane, at the same time several orbital planes can be achieved.

[View Full Paper]

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DESIGN AND KEEPING OF NANOSATELLITE-BASED HIGHLY ELLIPTICAL ORBIT FORMATION

Michael Koptev,* Sergey Trofimov,† Sergey Shestakov‡ and Yaroslav Mashtakov§

The problems of designing and keeping a highly elliptical orbit tetrahedron formation of one chief microsatellite and several deputy nanosatellites are examined. Initial orbital elements for all the spacecraft are searched to maximize a scalar formation quality factor introduced. The control scheme for the chief microsatellite is proposed to extend the overall tetrahedron formation lifetime. The deployment of an additional nanospacecraft is also considered for the same purpose. [View Full Paper]

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VECTOR MODEL OF MULTI-SATELLITE EARTH SURVEY AND ITS USE DIRECTIONS

Victor K. Saulskiy[*]

For total analysis of remote sensing satellite systems investigators should know all time intervals appearing during a given Earth latitude zone survey. In common case the task of time intervals determination is rather a complex problem. Its realization is usually achieved using various computer simulation methods. This way is very laborious. That's why investigators often calculate the only utmost time interval. In this work a universal analytical algorithm to calculate all time intervals and their frequencies for any satellite numbers and structures is offered. It is based on the special vector model of covering Earth latitudes with all satellite swaths.
Key words: vector model, satellite print, shag-vector, beta-vector, sub-model, satellite structure, ascending, descending, swath. [View Full Paper]

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FORMATION KEEPING STRATEGY FOR A QUASI-ZENITH GLONASS COMPLEMENT

V. V. Malyshev,[*] A. V. Starkov[†] and A. V. Fedorov[‡]

The work is executed at financial support of the Ministry of education and science of the Russian Federation in the framework of the state task (project No. 9.7505.2017/BCh) A quasi-zenith complement to improve GLONASS regional usability is under consideration. The study objective is to reveal the quasi-zenith constellation degradation as well as to work out formation keeping strategy to compensate dilution of positioning precision over 10-year period. [View Full Paper]

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THE MAINTENANCE OF A GIVEN CONFIGURATION OF A SYSTEM OF TWO SATELLITES

Nikita V. Chernov[*] and Vadim O. Vikhrachev[*]

We consider the problem of maintaining with high precision a given configuration of the satellite group consists of two units. [View Full Paper]

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ON OPTIMIZATION OF TWO-TIER WALKER DELTA PATTERNS SATELLITE CONSTELLATIONS TO PROVIDE CONTINUOUS COVERAGE OF NEAR-EARTH SPACE SPHERICAL LAYER

Yury N. Razoumny,[*] Oleg E. Samusenko[†] and Nguyen Nam Quy[‡]

The paper overviews the current status of optimization methods which are aimed, or could be partially used, for the solution of the problem of satellite constellation design for continuous near-Earth space global coverage. It reviews current basic terms and definitions as well as introduces new ones relevant to the problem mentioned. The new mathematical approach and methodology of optimization the compound, two-tier Walker Delta Pattern constellations to provide continuous near-Earth space coverage is presented. The examples of its practical implementation are presented as well. The advantages of two-tier Walker Delta Patterns, in comparison with classic one-tier Walker Delta Patterns, are shown for the problem discussed. [View Full Paper]

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