DYNAMICS AND CONTROL OF SPACE SYSTEMS DyCoSS'2018

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Front Cover Illustration:

The illustration shows the space view of the Earth, the nanosatellite “Tian-Tuo III,” and some other satellites and stars. Credit: College of Aerospace Science and Engineering, NUDT.

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Edited by
Ya-Zhong Luo
Jeng-Shing Chern
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FOREWORD

This volume of the Series Advances in the Astronautical Sciences is dedicated to the Fourth International Academy of Astronautics (IAA) Conference on Dynamics and Control of Space Systems – DyCoSS'2018 held in Changsha, China, May 21–23, 2018 and hosted by the National University of Defense Technology (NUDT) founded in 1953. NUDT is one of the top-level universities in China and it is successively designated to 211, 985, and Double-tops projects, the three national plans for promoting the development of Chinese higher education. Aerospace engineering is one of the oldest disciplines in NUDT, and contributes profoundly to China Artificial Satellite Project, Manned Spaceflight Project, Chang E Project, etc.

The Conference was sponsored by the IAA with the cooperation of the American Astronautical Society (AAS) and organized by NUDT. The theme of DyCoSS'2018 is "*Dynamics and Control make Space Systems Intelligent.*" During the conference, seven highlighted lectures on the hottest topics of space research were presented by Prof. Arun Misra, McGill University, Canada; Prof. Bong Wie, Iowa State University, USA; Prof. Guang Meng, Shanghai Academy of Spaceflight Technology, China; Prof. Filippo Graziani, Sapienza University of Rome, Italy; Prof. Xiao-Qian Chen, National Innovation Institute of Defense Technology, China; Prof. Eberhard Gill, Delft University of Technology, The Netherlands; and Prof. Lin Liu, Nanjing University, China..

DyCoSS'2018 attracted an unprecedentedly large number of scientists and engineers from all over the world: more than 300 participants from 20 countries and regions attended and provided an interesting forum for research in the field. Overall, 194 accepted articles were divided into 15 parallel sessions and 185 papers were actually presented by the authors. The present volume includes only the papers that were discussed during the DyCoSS'2018 sessions. The work of parallel sessions of DyCoSS'2018 began on May 21 and continued to the afternoon of May 23, 2018. The discussions were divided into "Satellite Constellations and Formation Flying„ "Spacecraft Guidance, Navigation and Control," "Attitude Dynamics and Control," "Space Mission Design and Optimization," "Orbital Dynamics and Orbital Determination," "Space Structures of Tethers," "Attitude Sensors and Actuators" and "Astrodynamics with Artificial Intelligence" in eight branch venues.

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 NUDT. We appreciated very much the dedication of the participants of DyCoSS'2018 (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'2018 Co-Chairs:
Prof. Ya-Zhong Luo
Prof. Jeng-Shing Chern
Prof. Xiao-Qian Chen
Prof. Lei Chen

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RECEDING-HORIZON CONTROL FOR THE LINEAR TIME-VARYING SYSTEM USING LEGENDRE-GAUSS-RADAU COLLOCATION METHOD

Siyuan Wang,[*] Cong Wang,[†] Yuxin Liao[‡] and Shibin Luo[§]

This paper presents alternative approximate optimal feedback control laws based on the Legendre-Gauss-Radau collocation method for online implementing the receding-horizon control strategy to the linear time-varying system. At each time step, with the aid of the differential Legendre-Gauss-Radau collocation method or the integral Legendre-Gauss-Radau collocation method, the receding-horizon control problem for the linear time-varying system is discretized into an equality constrained convex quadratic programming problem, and the current control input is obtained from the analytical solution of this convex quadratic programming problem. The resulting approximate optimal feedback control laws are appealing from the perspective of high accuracy with a few discrete points, and are appropriate to practical application for high computation efficiency and easily programming. Numerical simulation results of the satellite formation keeping problem demonstrate high performance of the proposed approximate optimal feedback control laws and the stability of closed-loop system. [View Full Paper]

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IAA-AAS-DyCoSS4-1-4
AAS 18-502

COLLISION-AVOIDANCE TRAJECTORY PLANNING AND TEST VERIFICATION OF CLOSE-RANGE SATELLITE FORMATION

Mingying Huo,* Naiming Qi,† Yufei Liu,‡ Shilei Cao,§ Zichen Fan§ and Yanfang Liu**

In the process of formation reconfiguration, the risk of collisions between satellites should be considered, especially for close-range satellite formation. In this paper, a virtual-potential method is proposed to avoid collisions in the formation reconfiguration. To verify the effectiveness, test verification of the proposed method is implemented using a formation control testbed. In this formation control testbed, there are 3 satellite simulators, which are used to simulate the dynamic interaction of satellite formations in a representative 3-DOF environment. Each satellite simulator is fully autonomous with compressed gas, battery power, and a complete suite of onboard avionics including cold-gas thrusters, reaction wheels, IMU and wireless links. The experimental results show that the pro-posed method can effectively reduce the risk of collision between satellites.

[View Full Paper]

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IAA-AAS-DyCoSS4-1-6
AAS 18-503

NONLINEAR FEEDBACK CONTROL OF THREE-CRAFT COULOMB FORMATION IN GEO

Tong Yu* and Shuquan Wang†

This paper investigates the three-craft Coulomb formation control problem in the geostationary orbit. The control problem is challenging because the system is nonlinear and nonaffine. The Coulomb forces and the conventional thrusters are utilized to control the formation to a desired triangular configuration, which is fixed in the Hill frame. The vector distance equations of motion of the formation are derived according to the linearized dynamics equations in GEO. In all situations, the isosceles is constrained to within a plane which is composed of two Hill-frame axes and the center of mass of the formation is located at the origin of the Hill frame. A Lyapunov-based nonlinear feedback control law is designed to stabilize the formation to the desired configuration. Numerical simulations illustrate the performance of the controller. [View Full Paper]

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IAA-AAS-DyCoSS4-1-8
AAS 18-504

SATELLITES FORMATION FLYING FOR PULSAR X-RAY INTERFERENCE MEASUREMENT

Qiang Chen,* ShaoLong Chen,† XiaoMin Bei,‡ HanWen Zhang§ and HengBin Zhang**

Pulsar navigation, can be applied to deep space navigation in future, which is influenced by the angle position of target pulsars. In this paper, the intensity interference method, to greatly improve the measurement precision of angle position, is given by a pulsar X-ray observation plan of using formation flying satellites. Firstly, the task and goal are pointed out. Secondly, the working principle, system framework and operation modes of the X-ray intensity interference measurement system by formation flying satellites are described sequentially. Thirdly, two formation flying structures are analyzed and compared in detail from spatial coherence, pulse profile folding time, space radiation etc. Finally, the key science and technology issues of the task are raised. [View Full Paper]

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IAA-AAS-DyCoSS4-1-10
AAS 18-505

MULTIPLE IMPULSIVE SPACECRAFT FORMATION RECONFIGURATION BASED ON THE ORBITAL ELEMENT DIFFERENCES DYNAMICS MODEL

WANG Youliang,* LI Mingtao,† MENG Yazhe‡ and ZHENG Jianhua†

Multiple impulsive spacecraft formation reconfiguration under J2 perturbation is studied, and the fuel-optimal strategy is developed based on nonsingular Gauss Variation Equation and mean orbital element propagation under J2 perturbation. Firstly, a linear relative dynamics equation using the nonsingular orbital element differences dynamics model is derived, which considers the J2 perturbation and the coupling effects between in-plane and out-of-plane relative motion. Thus, the formation reconfiguration problem can be described as a Mixed Integer Nonlinear Programming mathematical problem. Then, the hybrid approach of Differential Evolution algorithm and Sequence Quadratic Programming is proposed to optimize the total velocity increment. Finally, the efficient of the optimization result is proved with the Primer Vector Theory considering J2 perturbation, and the influence of transfer time and the reference orbital eccentricity on the total velocity increment is analyzed. The simulation results show that the hybrid approach is effective, and can obtain the feasible solution efficiently for both circular and elliptic reference orbit.

Keywords: Impulsive Formation Reconfiguration; Primer Vector Theory; J2 Perturbation; Differential Evolution; Nonsingular Gauss Variation Equation. [View Full Paper]

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IAA-AAS-DyCoSS4-1-11
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NEW SPACECRAFT FORCED FLY-AROUND FORMATIONS DESIGN BASED ON RELATIVE ORBIT ELEMENTS

XI Jiaqi,[*] ZHANG Ran, HAN Chao

In order to meet the needs of spacecraft on-orbit service missions to fly-around technology, we have investigated the control of forced spacecraft fly-around in this paper. The paper introduces the relative orbit elements proposed by Lovell, which are the basis of our investigation about the fly-around. The three fly-around formations, the bi-elliptic, the teardrop and the bi-teardrop, are introduced. Based on the relative orbital elements, the pulse control strategy of each fly-around formation is solved and we simulated the three configurations. Also we introduce the theory of solving the relative motion trajectory and make an example of the reconstruction about the fly-around configuration. Finally, the pulse size and fly-around distance of the three fly-around configurations are prepared and we complete some explorations on the optimization of pulse control strategies.

[View Full Paper]

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IAA-AAS-DyCoSS4-1-13
AAS 18-507

RESEARCH ON DYNAMIC EVALUATION METHOD OF INTER-SATELLITE SECURITY FOR SATELLITE FORMATION

Bei Wan,[*] Hua Chen,[†] Yao K. Du,[*] Wen Y. Wang,[‡] Yu B. He[†] and Jia Cui[§]

Since June 2010 the German TanDEM-X formation mission had been successfully implemented in orbit, a formation advantage for earth observation had finally came true. Due to the deputy is flying closely in the order of hundreds meters relative to the chief, formation security should be particularly considered. This paper proposes a dynamic Evaluation method of inter-satellite security combined with typical formation control task. Using the relative dynamics based on relative orbital elements and the characteristic parameters of typical formation tasks, the method completes the dynamic evaluation of relative state security margin between satellites. The work of this paper can provide security basis for formation control planning. In order to verify the proposed method practical, a simulation example is constructed with the state parameters related to the TanDEM-X mission. Simulation results show the method is effective. In fact, the method has been applied to China satellite project and will be validated in orbit in the near future.

[View Full Paper]

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AAS 18-508

ORBIT RAISING AND DE-ORBIT FOR COPLANAR SATELLITE CONSTELLATIONS WITH LOW-THRUST PROPULSION

Simeng Huang,[*] Camilla Colombo[†] and Franco Bernelli Zazzera[‡]

This paper deals with the planar transfer problem (i.e. orbit raising and de-orbiting phases) for low Earth orbit coplanar satellites constellation. The objectives are to minimize the total time of transfer and to maximize the miss distance during these phases so as to minimize the collision hazard. A Blended Error-Correction (BEC) steering law, consisting of tangential thrust and inertial thrust based on the offset in mean orbital parameters, is developed to design the transfer trajectory for a single satellite. The semi-analytical technique is used to evaluate the variation in orbital parameters over one orbit revolution to reduce the computation load. The numerical results show that the BEC steering law is able to identify near time-optimal solutions and the semi-analytical results have good accuracy. For multiple satellites transfer, the orbit transfer trajectory designed for a single satellite is used as a baseline for a global multi-satellite analysis of the miss distance among pair satellites during the orbit raising and de-orbiting phases. Considering limits on the transfer starting time for de-orbit mission, multi-objective optimization is used to find out the optimal transfer starting time for each satellite. [View Full Paper]

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COLLISION-AVOIDANCE AUTONOMOUS CONTROL ALGORITHM FOR MULTI-SPACECRAFT PROXIMITY OPERATIONS

Dan-Dan Xu,* Jing Zhang† and Ya-Zhong Luo

A collision-avoidance autonomous control algorithm for multi-spacecraft proximity operations is proposed. First, an on-orbit service scenario with multiple cooperative service satellites and one uncooperative target is built. The service satellites can communicate with each other and have different job assignment. Some, called Observers, execute proximity observation and relative state measuring, and the others, called Oilers, and execute rendezvous and refueling. Second, an improved Artificial Potential Field (APF) method is used to design the control algorithm for the service satellites. The repulsion potential, standing for the collision with other service satellites, is designed based on the collision probability of error ellipsoids, rather than the relative distance. For an Oiler, the relative distance of the attraction potential is measured between its current state and the target. For an Observer, the relative distance of the attraction potential is measured between its current state and the standard configuration state. A simple strategy to decide the satellite to execute collision-avoidance maneuver (MAC) in two to-be-collide satellites is proposed based on the fuel and the distance to the target. Numerical simulations are executed to validate the proposed method. The results show that the proposed method can improve the safety and efficiency of the multi-spacecraft proximity operations. The effects of the major mission parameters, such as the number of service satellites, the error level, and the time delay of control, are successfully revealed by the comparison between different examples. [View Full Paper]

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AAS 18-510

A LOCAL ENHANCEMENT METHOD OF DECENTRALIZED ORBIT DETERMINATION FOR LARGE-SCALE LEO SATELLITE CONSTELLATIONS

CHEN Haiping*

In this paper, a local enhancement method of decentralized orbit determination for large-scale LEO satellite constellations is discussed. The main idea of this method is using the local information of nearby satellites, which include the observed the relative distance and velocity, to improve the precision of orbit determination. Different from the decentralized method, this paper formulates single consensus schemes of decentralized EKF to orbit determination autonomy. It formulated the dynamic graph to represent a hybrid distributed wireless sensor network made of internet satellites, which labeled the target and the nearby surveillance nodes. We put forward single consensus schemes of decentralized and collaborative framework in which each node in the network updates its tracking estimate of an object based on its own observations via extended Kalman filter. For nonlinear system, the single consensus of decentralized unscented Kalman filter is also discussed. The single consensus algorithm is defined that only one kind of information data achieve the consensus, the collaborative update stage is embedded in the decentralized estimation filter. According to the cooperative step's procedure, three different modified diffusion strategies are formed, Front Cooperative scheme, Middle Cooperative scheme and Back Cooperative scheme. The FC and BC look alike, but the performances have differences. The performance of different schemes is analyzed. Mean-square performance analysis of this method is analyzed. [View Full Paper]

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SPACECRAFT SWARM RECONFIGURATION BASED ON CENTRALIZED PLANNING AND ARTIFICIAL POTENTIAL FIELD FEEDBACK

Wen Feng,[*] Shuquan Wang[†] and Hongen Zhong[‡]

This paper investigates the optimal reconfiguration of spacecraft swarm. The traditional spacecraft formation specifies the target point with each spacecraft and then converts the reconfiguration problem into a path planning problem. As the number of the swarm increases, a more optimal solution can be obtained by matching the target point with the spacecraft one by one. In this paper, the geometries of the expected configuration are specified without specifying the expected locations of individual spacecraft. The first step is to select an optimal match to minimize the maneuver time of the reconfiguration mission. This paper uses the genetic algorithm to find the optimal match, with the time taken as the target function. Next, a Lyapunov based nonlinear controller with the awareness of collision avoidance is developed to accomplish the reconfiguration process. Owing to the reconstruction process running in a geostationary orbital environment, the dynamic equations are established in the Hill coordinate system. The reconfiguration process is a Rest-to-Rest process. The Lyapunov function is defined using the condition that each spacecraft reaches the target point with zero speed. To achieve avoidance of potential collision with fixed obstacles and neighboring spacecraft, the Lyapunov's method is extended to artificial potential functions, which generates repulsive forces from the obstacles and neighboring spacecraft. With the negative derivative of the Lyapunov energy function, the "repulsion" force of the artificial potential functions and the angular velocity produced by gravity, nonlinear controller are set up to accomplish the path-planning of the reconfiguration mission. The numerical simulations show that spacecraft swarm reconfiguration based on time-optimal centralized planning and artificial potential field feedback is effective. [View Full Paper]

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AAS 18-512

OPTIMAL MANEUVER PLANNING FOR THE CO-LOCATION OF GEOSTATIONARY SATELLITES

Sumeet Satpute[*] and M. Reza Emami[†‡]

This paper addresses the problem of determining optimal station keeping and momentum unloading maneuvers for a fleet of satellites co-located in a specific geostationary slot. A leader-follower architecture is implemented to control the motion of the follower satellites relative to the leader satellite. A convex optimizationbased algorithm is proposed to determine the concurrent maneuver planning for the satellites equipped with four on-off electric thrusters. The main objective of the maneuver planning algorithm is to minimize fuel consumption while guaranteeing a safe separation distance between the co-located satellites, as well as managing the stored angular momentum, in order to maintain nadir pointing orientation of each satellite. The proposed algorithm is verified in terms of fuel consumption and constraint enforcement, using numerical simulations that take into account dominant perturbations in the geostationary environment. [View Full Paper]

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AAS 18-513

SATELLITE CONSTELLATION DESIGN FOR MULTI-TARGET REMOTE SENSING MISSION

Zhanyue Zhang,[*] Haitao Zhang[†] and Shuai Wu[†]

For the mission of achieving a maximum revisit interval of less than 1 hour for multi-target within a given area on the ground with as few satellites as possible, and try to ensure that the revisits are evenly distributed, the first satellite orbit is designed using the two-body model. The satellite can achieve two observations of the same target point within one day, and then the mission satellite constellation is designed. To calculate the perturbation of the satellite, J_2 perturbations must be considered in a time scale of one week. The influence of J_2 perturbation on the satellites for this mission is mainly reflected in the change of orbit's right ascension of ascending node (RAAN). Calculate the influence of J_2 perturbation on the RAAN and guide the amendment of the semi-major axis of the orbit to realize that the satellite can observe the same target point twice a day and then design the constellation to accomplish the mission. [View Full Paper]

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:
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Binfeng Pan
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Yu Jiang
Hongxin Shen

IAA-AAS-DyCoSS4-2-3
AAS 18-514

A REVISIT OF THREE-DIMENSIONAL LINEAR-TANGENT GUIDANCE LAW FOR PAYLOAD MAXIMIZATION

Jeng-Shing (Rock) Chern[*] and Ke-Qin Huang[†]

Early applications of the complicated guidance and control laws were strongly limited by the capacity and speed of onboard computer. Modern electronic and computer technologies have eliminated most of the difficulties. The launch vehicle guidance and control technologies have been developed for more than one half of a century. Development of launch vehicle technology has been mature and the accuracy of guidance and control is getting better and better. Among the various launch vehicle guidance laws, the linear-tangent guidance (LTG) was developed in the 1960s. Basically it is a parameterized guidance law for launch vehicles. This paper revisited and investigated the design and simulation of a three-dimensional LTG for payload (PL) maximization. A nominal trajectory without any disturbance was generated at first. Then a normal disturbance force with 45-degree offset angle is added to calculate a three-dimensional perturbed trajectory. And then the LTG was imposed to guide the launch vehicle back to the nominal trajectory for PL maximization by adjusting the LTG parameters. For simulation purposes, a typical launch vehicle model was used. Under nominal condition, the satellite mass was assumed to be 1,000 kg with a circular orbit altitude at 646 km. After maximization, the maximum PL obtained was 1,170 kg even under normal force disturbance, an increase of 17%. Precise orbit insertion could be achieved with the maximized PL. [View Full Paper]

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ANTI-COLLISION COOPERATIVE CONTROL STRATEGY FOR MULTI-AGENT BASED ON COLLISION PROBABILITY

Yuanhe Liu,* Yangang Liang† and Kebo Li‡

The calculation of collision probability between multi-agent is the basis for the agent to prevent collision warning and make evasion maneuver. In this paper, a method of calculating the collision probability is proposed, and the integral calculation formula is simplified as an algebraic expression. Then the impact of the position error, the safety radius and the relative distance on the collision probability is analyzed. Finally, collision probability is applied to anti-collision control among agents, and simulation proves that the scheme of anti-collision control can effectively reduce the maximum collision probability between agents. [View Full Paper]

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DIRECT/INDIRECT DISTURBANCE REJECTION CONTROL FOR AIR-BREATHING HYPERSONICVEHICLES

Lin Cao,* Dong Zhang† and Xiang Wang‡

Considering the inertial uncertainties and external disturbances of air-breathing hypersonic vehicles (AHVs), the flight control system of AHVs can be simplified as the general control issue for an uncertain nonlinear system with mismatched disturbances. In order to achieve the target of disturbance rejection, this paper proposes direct and indirect disturbance rejection control approaches to investigate the flight control of AHVs. For different levels of system disturbance, the typical direct and indirect disturbance rejection control schemes are presented and compared with each other. Finally, simulation results illustrate the advantages and application limits of the direct and indirect disturbance rejection control approaches. [View Full Paper]

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AAS 18-517

A MULTI-INFORMATION NUMERICAL PREDICTION-CORRECTION REENTRY GUIDANCE METHOD FOR SUBORBITAL REUSABLE LAUNCH VEHICLE

SUN Peng,* QIAO Hao† and LI Xinguo‡

In numerical prediction-correction (NPC) reentry vehicle guidance method, the control commands-bank angle need to be searched online, and the traditional search algorithm is in generally based on iterative method which requires the gradient information of range and bank angle. The uncertainty of the calculation time in the iterative method affects the reliability and stability of the NPC guidance method, thus limits the application put into use.

This paper presents a multi-information numerical prediction-correction (MINPC) guidance method without iterations, which is also easy to parallelize. Using this method, multi-mode accessible region of the vehicle can be initially generated by direct shooting (DS) method. Then the value of bank angle calculate by following the rules, that it should make the target point of vehicle is in the accessible region generated before. Meanwhile, the sign of bank angle is determined by a new lateral guidance logical which is perfect match the MINPC. Thereby, the MINPC guidance method can satisfy the time constraints of generating guidance command in real time. In addition, we implement the MINPC algorithm with a Compute Unified Device Architecture (CUDA) device. Finally, some numerical simulations are carried out for different mission scenarios with significant dispersions, suggesting that the new method is capable for the suborbital reusable launch vehicle (SRLV) reentry guidance mission. [View Full Paper]

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AAS 18-518

AN ADAPTIVE ESTIMATION ALGORITHM OF LINE-OF-SIGHT (LOS) RATES USING STRAPDOWN SEEKER MEASUREMENTS IN HOMING GUIDANCE

Kunkun Li,[*] Lei Chen[†] and Kebo Li[‡]

The line-of-sight (LOS) rates information is of importance to guidance commands of missiles using proportional navigation (PN) law during terminal homing guidance. In this paper, the LOS rates estimation problem in the exoatmospheric air-to-air combat scenario with regard to a maneuvering target is studied. And then using the strapdown seeker measurements, an adaptive estimation algorithm, based on the modified current statistical (CS) model and interacting multiple model (IMM), was proposed. Monte-Carlo simulations are implemented to demonstrate the feasibility and validity of the proposed algorithm. [View Full Paper]

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NOVEL AUGMENTED PROPORTIONAL NAVIGATION GUIDANCE LAW FOR MID-RANGE AUTONOMOUS RENDEZVOUS

Ke-Bo Li,[*] Yuan-He Liu[†] and Lei Chen[‡]

In this paper, a novel augmented proportional navigation guidance law (APN) is proposed for the mid-range autonomous rendezvous. This guidance law consists of two parts. The first one is a nonsingular terminal sliding mode control (NTSMC) law along the line of sight (LOS) where a sliding surface is designed to drive the relative distance and approaching speed between the chaser and the target to zero in finite time. The second one is the traditional true proportional navigation (TPN) guidance law along the normal direction of LOS to control the LOS rate in a certain range. It is proven that, even when there are disturbances and uncertainties along and perpendicular to LOS respectively, the proposed APN can assure the finite time convergence of the relative distance, and the LOS rate can be limited in a certain acceptable range. The new theoretical findings are demonstrated by numerical simulation results. [View Full Paper]

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STUDY ON THE STABILITY INDEX OF HYPERSONIC VEHICLE'S NONLINEAR LONGITUDINAL SYSTEM BASED ON MANIFOLD METHOD

WU Pengwei,* LI Yinghui,† ZHENG Wuji,‡ ZHOU Chi§ and DONG Zehong**

Considering the seriously nonlinear and coupling characteristics of supersonic vehicle, the frequency domain method, which is at the basis of the linear theory and widely used in the designing phase, is limited under this condition. The manifold method, which can obtain the exact region of attraction based on the nonlinear control theory, is proposed to analyze the stability of supersonic vehicle. Firstly, the manifold theory is introduced, and the stability boundary for nonlinear longitudinal dynamic system of hypersonic vehicle is determined by manifold method. The anti-interference ability of the working point and the size of the stable regions are analyzed via using the distance between working point and unstable equilibrium point on the stable boundary. And then the relationship between the distance and the design index in frequency domain is studied in detail. The results show that the law can be expressed as an equation; and the distance can be regarded as a substitute of the design index for a seriously nonlinear and coupling dynamic system, which can provide the basis for performance design of the supersonic vehicle on the preliminary phase. [View Full Paper]

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AN ASCENT TRAJECTORY DESIGN AND GUIDANCE APPROACH FOR A SCRAMJET POWERED VEHICLE

Jianhui Liu[*] and Mingang Zhang[†]

In this paper, the trajectory design and guidance problem is addressed for the ascent phase of a test scramjet powered vehicle subject to the maximum and minimum dynamic pressure constraints and other constraints. For the ascent trajectory, the thrust and fuel consumption models of the engine, vehicle's aerodynamic models and the dynamics models are formulated. The angle of attack and the equivalence ratio are chosen as trajectory control variables and determined. Based on a linear ascent acceleration assumption, the flight time of ascent trajectory is determined from the initial and terminal velocities, and then is divided in-to small time intervals. In every time interval, the angle of attack and the equivalence ratio of engine are sequentially solved from a system of nonlinear dynamic equations by Broyden's algorithm. Based on the designed nominal altitude, angle of attack, and equivalence ratio profile, a feedback control guidance scheme is supposed for tracking and control to the perturbed trajectory. Numerical results for a test vehicle are provided and discussed, demonstrating the effectiveness of the proposed trajectory design and guidance method. [View Full Paper]

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GUIDANCE AND CONTROL ANALYSIS FOR POWERED DESCENT AND LANDING OF A VTVL ROCKET

Qingzhong Gan,* Peng Wang† and Huayun Shi‡

In the past decade, a vertical takeoff and vertical landing (VTVL) rocket recovery has come to the forefront of the aerospace industry and academic research. One of the key challenges posed by VTVL rockets precision landing is the powered descent and landing technology, which can serve both to dramatically de-creasing the cost of space transportation and to provide alternative scheme for planetary precision landing such as the future Mars pinpoint landing missions. In this paper, to evaluate the ability to perform a guided descent and landing of a VTVL rocket actuated by a single gimbaled rocket engine with lower and upper thrust bounds, the guidance and control scheme is developed and analyzed. More specifically, the powered descent guidance algorithms based on E-guidance, including the Apollo version and the higher-order version, are firstly formulated and compared. One result of this compare and analysis is that the requirement of divert capability does not allow the use of a quadratic algorithm, such as that used by the Apollo lunar module, but instead requires a higher-order guidance approach. Furthermore, to obtain the improved performance, a simple yet effective strategy is used to yield predictable aerodynamic accelerations which would be formatted into guidance. The control scheme is then designed and incorporated, along with the powered descent guidance algorithm, into a six-degree-of-freedom simulation. Six-degree-of-freedom simulations are conducted at last to assess and demonstrate the capability of this VTVL rocket to successfully execute a powered descent and landing on the designated location within the propellant budget when encountering off-nominal initial condition, off-nominal thrust and aerodynamic coefficient uncertainties. [View Full Paper]

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SWITCHING CONTROL COMBINING PID CONTROL AND ADAPTIVE PID SLIDING MODE CONTROL BASED ON NEURAL NETWORK FOR VARIABLE CONFIGURATION SPACECRAFT

Ran Wang,[*] Zhicheng Zhou and Guangji Qu

During the configuration variation of the spacecraft with flexible appendages, the mass distribution of the spacecraft will change significantly, and this will perform big disturbance to the attitude of the spacecraft. The widely used PID controller cannot perform well in the process of configuration variation, to solve this problem, a novel controller combining PID control and sliding mode control is proposed in this paper. To combine the two kinds of control methods, the relationships between parameters of PID control and parameters of sliding mode control with PID sliding surface are derived. The control system will switch to sliding mode control during the variation of the spacecraft configuration, when the variation ends, the control system will switch back to PID control to avoid the chattering of the sliding mode control. The range of PID control parameters can be obtained from the relation of the control parameters, dynamical parameters and system bandwidth, and RBFNN (Radial Basis Function Neural Network) with PSO (Particle Swarm Optimization) method is used to tune parameters of the sliding mode controller with PID sliding surface during the configuration variation to improve the control performance. The stability of the system is demonstrated by Lyapunov theorem. Finally, simulation results verify the effectiveness and practicability of the controller combining PID control and PID sliding mode control, and comparisons are made to verify the good properties of the proposed controller. [View Full Paper]

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RESEARCH OF GUARANTEED CONTROL OF THE SPACECRAFT IN ELLIPTICAL ORBITS

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The problem of constructing control for a spacecraft in an elliptical orbit is considered. The dynamics of the movement of the spacecraft is described by nonlinear differential equations. The problem of controlling synthesis is solved using the principle of guaranteed control and quadratic quality functional. As a result of the research, a regulator is obtained, which makes it possible to synthesize control, the physical meaning of which is to stabilize the spacecraft in a given orbit and transfer from one orbit to another. A method for solving the first-order nonlinear partial differential equation (the Hamilton-Jacobi-Isaacs equation) for building control of a nonlinear, indeterminate dynamic object is developed. In order to check the effectiveness of obtained solutions, mathematical modeling is performed, and the results of which are also presented. [View Full Paper]

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REENTRY GUIDANCE FOR AEROSPACE BASED ON REAL-TIME ANALYTIC CONSTRUCTION

LIU Zhiyong,[*] HE Yingzi[†] and FAN Songtao[‡]

A reentry guidance technology based on real-time analytic construction is proposed with multiple process constraints and high precision terminal state were needed. First of all, A guidance control model satisfied the process constraints and terminal state precision was established, and guidance model parameters were solved in real-time; then, based on the real-time generation of reentry guidance model, a guidance law was designed based on the nonlinear control method, and it was proved the closed-loop stability; finally, the simulation results show that the guidance method proposed in this paper has the characteristics of strong robustness and high precision. [View Full Paper]

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OBSERVABILITY ANALYSIS AND AUTONOMOUS NAVIGATION FOR TWO SATELLITES WITH RELATIVE POSITION MEASUREMENTS

Yong Li* and Ai Zhang†

The relative and absolute positions estimation of multi-satellite system using only on-board measurements is a fundamental task in many space missions. The main purpose of this paper is to develop methods for estimating absolute and relative positions of two satellites using relative position vector only. k-order local weak observability as a new concept is proposed and introduced into analysis. For unperturbed Kepler orbit dynamics models and J2-perturbed orbit models, sufficient and necessary conditions of k-order locally weak observability of the autonomous navigation system are presented and mathematically proved respectively. Furthermore, observability-based modified EKF, modified UKF and modified SDREF are designed and applied as navigation algorithms for simultaneously estimating the two satellite orbits. Several simulations are shown to verify the result on observability analysis, and to demonstrate that observability-based navigation algorithms can significantly improve the accuracy of the proposed system.

[View Full Paper]

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AUTONOMOUS NAVIGATION BETWEEN DISTANT RETROGRADE ORBITS AND EARTH ORBIT SATELLITES USING ONLY RELATIVE RANGE DATA

Wenbin Wang,[*] Chao Peng,[†] Jiangkai Liu,[‡] Leizheng Shu[§] and Yang Gao[**]

Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) technique uses only relative satellite-to-satellite tracking measurement to achieve absolute orbit solutions when at least one satellite is placed in the asymmetrical gravity field of the three-body system. Previous studies have shown its viability to carry out various navigation missions when considering a satellite in a halo orbit. However, the halo orbits are not stable and need orbit station keeping maneuvers constantly, they are not suitable for long-term navigation mission. A family of distant retrograde orbits (DROs) are large orbits around the Moon in the Earth-Moon three-body system. DROs in the vicinity of the Moon experience strong asymmetrical gravity similar to the halo orbits but with characteristic of long-term orbit stability, even excesses 500 years. This paper demonstrates the viability of autonomous navigation using only the relative range data between a DRO satellite and the satellites placed in the Earth orbits, including GEO, MEO and LEO. An extended kalman filter method was used to process the relative range data with 1-meter measurement errors and dynamical model errors, including the Earth gravity, SRP, and atmospheric drag. The results show that the position accuracy of the Earth satellites can achieve meters-level, except that the gravity error decreases the position accuracy of LEO to 80 m. Different dynamical errors and different tracking satellites will result in different position accuracy of DRO, which ranges from meters-level to 190 m. So, a satellite in a stable DRO has the feasibility of providing accurate positions service to Earth orbit satellites autonomously. [View Full Paper]

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AUTONOMOUS NAVIGATION OF HEO SATELLITES FORMATION BASED ON A SERIES FILTER

Yunpeng Hu,* Kebo Li† and Lei Chen‡

HEO satellites are widely used in many missions due to their special orbital characteristics. To improve their application value, HEO satellites formation may be a direction. This paper designs a series filter for autonomous navigation of HEO satellites formation. According to the navigation characteristics of HEO satellites, the whole navigation is divided into two parts, i.e. perigee stage and apogee stage. When HEO satellites run in the perigee stage, they have good observabilities for GPS satellites. And UKF is used in this stage to obtain accurate navigation results for HEO satellites by multiple GPS measurements. At the end of this stage, accurate prior information can be provided for the apogee stage where the observation condition of HEO satellites for GPS satellites is bad. In the apogee stage, HEO satellites use the inter-satellite ranging system to perform autonomous navigation missions with the support of the prior information. In this stage, a linearized system is established based on the T-H equation state transition matrix. And linearized KF is used to reduce the calculation burden. By simulation, the performance of proposed filter is demonstrated. Although the linearized filter will cause the declination of the navigation accuracy at the end of the apogee stage, it can be modified when HEO satellites come back to the perigee stage. [View Full Paper]

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ACTIVE DISTURBANCE REJECTION CONTROL AND OPTIMAL DIPOLE SOLUTION FOR MULTI-CRAFT ELECTROMAGNETIC FORMATION

Mingqi Yang,[*] Min Hu,[†] Jiahui Xu[*] and Guangyan Guo[*]

Compared with traditional distributed spacecraft depending on thrusters, the mission life can be prolonged and plume contamination can be avoided using electromagnetic formation flying (EMFF). However, an electromagnetically controlled spacecraft system is nonlinear and coupled, and the electromagnetic force/torque model is uncertain. Firstly, a configuration for four spacecraft is designed. Then an active disturbance rejection controller for reconfiguration of multi-craft EMFF is proposed. Finally, an optimal dipole solution is derived. The magnetic moment allocation problem is transformed to a nonlinear con-strained optimization problem, and then this problem is approached using simulated annealing, thus an optimal dipole solution is obtained. [View Full Paper]

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FINITE TIME SLIDING SECTOR CONTROL FOR SPACECRAFT ATMOSPHERIC ENTRY GUIDANCE

Biao Xu,* Shuang Li,† Weihua Wang‡ and Tianfu Lin§

The paper presents a novel variable structure control with finite time sliding sector for spacecraft atmospheric entry guidance. The finite time convergence of tracking error in the presence of system uncertainty can be guaranteed. In contrast with the normally used notion of asymptotic stability in conventional sliding sector, a finite time sliding sector is defined as a subset of state space in which the Lyapunov function candidate satisfies the finite time stability condition. Then, the finite time sliding sector controller is designed to guarantee the tracking error to converge to a small region of zero. The chattering existing on the boundary of the sliding sector is further reduced by replacing the signum function with the saturation function. Finally, numerical simulation results are given to demonstrate the effectiveness of the proposed method. [View Full Paper]

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COMBINED STATION KEEPING OF INCLINATION AND LONGITUDE FOR GEOSTATIONARY SATELLITE WITH ELECTRIC PROPULSION SYSTEM

Lincheng Li,* Jingrui Zhang† and Shuge Zhao‡

Station keeping is a prerequisite for the on-orbit service of geostationary satellites. It can restrain the drift caused by high-orbit perturbations effectively and increase the on-orbit stability. Using electric propulsion to achieve station-keeping has the advantage of reduction in the fuel consumption. This paper is to develop a station keeping strategy to solve the combined control for inclination and longitude. High-precision equation of motion described by mean orbital elements is proposed in the first part. Then the fuel-optimal control is applied to indicate the relation among switching time of four thrusters. Thus, the equation between variation of orbital elements and speed increment can be analytically solved. Finally, numerical results are presented to evaluate this technique.

[View Full Paper]

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A METHOD FOR RAPIDLY SOLVING THE SHORTEST DOWNRANGE PROBLEM OF ENTRY VEHICLE UNDER MULTIPLE CONSTRAINTS

Ming Liu,* Ming Yang,† Lingxiao Yang,‡ Ding Yang§ and Erlong Su**

In order to maximize the coverage of entry vehicle, this paper studies shortest downrange problem and rapidly solving method under constraints of heat and control. Firstly, based on path constraints, we introduce the control of the angle of attack (AOA), establish the Three-Dimensional Angle of Attack-Altitude-Velocity (3D-AAV) entry corridor, and derive the logarithmic entry corridor boundary. Secondly, based on the logarithmic entry corridor, we acquire the analytic solution of the shortest glide range and the flight mechanism for obtaining the maximum turning amplitude. Finally, we design a strategy of iterative generation of the shortest downrange analysis based on analytic solution. Based on the analytic solution, this method realizes rapidly searching and solving the shortest downrange of entry vehicle, which has great engineering application value.

[View Full Paper]

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H_∞ LOOP SHAPING CONTROLLER FOR FLEXIBLE SPACECRAFT

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Aiming at the attitude control problem of flexible spacecraft for uncertainties caused by the rotation of solar panels, H_∞ loop shaping based on interval algorithm is investigated and a nominal design method is proposed. The dynamic model of flexible spacecraft is given by means of the linearized hybrid coordinate equation. According to the maximum singular value algorithm of complex interval matrix, and the normality of dynamic model of flexible spacecraft, the upper and lower bound of the singular value of the uncertain system can be obtained. Based on the upper and lower bound calculated above, a low-order transfer function of nominal system can be fitted by amplitude-frequency fitting method. Then, based on the classical H_∞ loop shaping idea, the resulting low-order nominal system is used to design controller. A numerical simulation ex-ample is given to verify the effectiveness of the proposed method. [View Full Paper]

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A RELATIVE NAVIGATION METHOD BASED ON ORBIT MANEUVER COMPENSATION FOR SPACE NON-COOPERATIVE MANEUVERING TARGETS

TAN Tian-le,* ZHANG Xiao-tong† and SUN Jian-dang‡

In recent years, relative navigation technology of moving objects, spacecraft, debris and other space objects has become a research hotspot. In relative guidance process of constellation deployment, satellite formation and space manipulation, it is worth studying how to realize the relative navigation of noncooperative targets that with orbit maneuver, and to track relative position and relative speed accurately and timely. In this paper, a relative navigation algorithm based on maneuver estimation and compensation is proposed to overcome the shortcomings of the original filtering method which has no navigation feedback and reduce the errors of maneuvering navigation. Through relative dynamics modeling and solving, the law of relative motion state evolution is obtained. The acceleration of the orbit maneuver of the target spacecraft is estimated by the generalized inverse theory. The maneuvering acceleration is feedback to the filter and the previous filtering results are fully utilized to achieve the fast tracking of maneuvering targets. Simulation shows that the proposed method can accurately estimate the orbit maneuver of noncooperative space targets. The relative navigation error of target maneuver is far less than that of conventional extended kalman filter, and the convergence time of navigation is shorter.
[View Full Paper]

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SPACE GNC SEMI-PHYSICAL SIMULATION SYSTEM BASED ON DUAL 6-DOF MECHANISM IN A MICROWAVE ANECHOIC CHAMBER

Jiadong Ren[*] [†] [‡], Zhijie Shao,[†] [‡] Zhu Wenshan[†] [‡] and Qingshuang Zeng[*]

With the development of space technology, the on-orbit serving (OOS) research of spacecraft has been a hotspot in the space agencies of various countries. It is usually very dangerous in the execution of space tasks, especially space rendezvous and close control. Ground test verification of the OOS technology is essential in the implementation of space tasks. In order to verify the technology of space rendezvous and acquisition based on the photoelectric/microwave tracking equipment, the test system framework of the dynamic truss structure and the solar simulator, which has limited motion dimension and low spatial environment fidelity, is given by the FRL laboratory in the United States. Nevertheless, this paper proposed a novel test system framework of dual 6_DOF mechanism structure in microwave anechoic chamber, which gives consideration to tracking equipment of microwave/optical mechanism and completes the high precision simulation of on-orbit relative motion of spacecraft and spatial target RCS / LRCS. The test system in the paper can be used to verify the whole task process of space rendezvous, approaching, stopping, and so on. Finally, a simulation test is given to verify the effectiveness of the proposed system framework in the paper. [View Full Paper]

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UNCERTAINTY PROPAGATION OF REENTRY TRAJECTORY UNDER PIECEWISE CONTINUOUS CONTROL

Xiangyue He,[*] Haiyang Li[†] and Yuechen Huang[‡]

Reentry is an important phase for the vehicle returning to the Earth, and uncertainty propagation in reentry dynamics has become a hot topic in recent years. The main task of this paper is to investigate the statistic characteristic of the reentry trajectory with crossrange corridor under parameter uncertainties. Specifically, the non-smooth feature of the lateral control with crossrange corridor, which is shown as the reversal of the bank, is mainly considered. Hence the control law turns to be a typical piecewise continuous function, and the uncertainty propagation becomes nonlinear. The nonintrusive polynomial chaos expansion based method and the Monte Carlo simulation are introduced for the analysis. Results show that the distribution of the final crossrange would be obviously impacted by the crossrange corridor, which won't fit the same distribution of the initial parameter uncertainties. Our research can provide a theoretical basis for the analysis of the reentry trajectory uncertainty propagation. [View Full Paper]

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ENERGY MANAGEMENT METHOD OF ENTRY VEHICLE BASED ON SINGLE-SIDED BANK STRATEGY

Ming LIU,[*] Ming YANG,[†] Ding YANG,[‡] Yajie GE[§] and Xiaoli QIN[**]

The entry vehicle is used to make energy manage by changing aerodynamic drag when it flies in the atmosphere, and the aerodynamic drag is restrained by constraints of heat and control, which causes that the energy management capability of the aircraft is limited. In order to further improve the energy management efficiency of entry vehicle under multiple constraints, this paper proposes an energy management method based on Single-Sided Bank Strategy (SSBS) under constraints of forces, heat and control which uses basic law of spherical geometry. Firstly, taking the minimum flight downrange as the performance index, the three dimensional trajectory of entry vehicle without constraints is obtained based on pseudospectral method. Secondly, a guess for the trajectory of multiple constrained minimum downrange under Single-Sided Bank Strategy (SSBS) is proposed, and the correctness of the guess is proved based on the basic law of spherical geometry. Finally, the influences of constraints such as force, heat and control on energy management efficiency is analyzed. This method applies the basic law of spherical geometry to the trajectory characteristics of entry vehicles, and expands the energy management efficiency under multiple constraints, which has a great engineering application value.

[View Full Paper]

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DATABASES FOR HUMAN-INSPIRED TRAJECTORY PLANNING AND STATIONKEEPING AT BINARY ASTEROID SYSTEMS

Davide Guzzetti* and Hexi Baoyin†

Within binary asteroid systems, identification of trajectory design and stationkeeping strategies that are robust to uncertainties and reusable at many asteroids is an open challenge. Solutions to this problem may stem from observing human agents controlling in real-time spacecraft motion within a variety of asteroid systems. Human agents tend to naturally generalize path-planning processes to new situations. This work explores how such a human mental quality applies to orbit dynamics within binary asteroid systems. In a simple flight simulator, human agents are observed while steering in real-time the spacecraft trajectory to maximize a given scoring function, one that represents the degree of mission success. Several simulations reveal efficient and effective trajectory planning and stationkeeping decisions that apply to a large spectrum of asteroid systems. The recording of these simulations forms a reference database, one that may serve in successive studies and may supply insight into autonomous spacecraft guidance. Databases of human-driven trajectories may, in fact, offer information to improve existing guidance schemes and foster new approaches, including those derived from machine learning.

[View Full Paper]

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RANGE-ONLY RELATIVE NAVIGATION FOR PERIODIC MOTION DURING CLOSE-IN PROXIMITY OPERATIONS

Baichun Gong,[*] Junjie Shi,[†] Wendan Li[‡] and Yang Yang[§]

Range-only Initial relative orbit determination (IROD) for periodic relative motion suffers from a well-known mirror solution problem when linear dynamics used during coasting flight. One approach proposed in previous work is to perform specific orbital maneuvers so as to avoid ambiguous relative state estimates. Alternatively, if the range-sensor offset from the spacecraft center-of-mass (COM) is considered, the relative orbit may be determined by using range-only measurements. This research developed a novel analytic solution to the range-only initial relative orbit determination problem for natural periodic relative motion during close-in proximity operations by utilizing the range-sensor offsetting for enhanced observability to exclude mirror solutions while using attitude maneuver to construct analytic solution. As a result, the initial relative orbit determination is reduced to a problem of solving equations. Based on these equations, the analytic solution for the relative state is explored. Overall, it has been strictly theoretically proved the range-only problem of periodic coasting close-in operations can be analytically solved. All these theoretical results are verified by a set of numerical simulation examples.

[View Full Paper]

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A FIXED-TIME TERMINAL SLIDING-MODE CONTROL FOR MARS ENTRY VEHICLE

WEI Haogong and WANG Qiang*

This paper presents a novel fixed-time terminal sliding-mode control (TSMC) for Mars entry vehicle with system uncertainties and external perturbations. A newly defined non-singular terminal sliding surface is constructed and a guaranteed closed-loop convergence time independent of initial states is derived based on the phase plane analysis and Lyapunov tools. The performance of the guidance methodology is verified by simulations of a Mars entry vehicle in the end. [View Full Paper]

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ADAPTIVE MULTI-PASSIVE CONTROL FOR DIFFERENT ALTITUDE SUBTASK OF SUN-SYNCHRONOUS ORBIT

LI Zhiwu[*] and TAN Tian[†]

To ensure good sun-synchronous properties, usually the altitude of sun-synchronous orbit (SSO) corresponds with inclination one by one. The local time passing descending node (LTDN) will drift quickly when the altitude of SSO changed a lot after launch. In order to avoid the huge fuel cost for maintaining the sun-synchronous properties by correcting the inclination and the right ascension of ascending node, the altitude of each mission is almost the same during its life. At present, the satellite lifetime becomes longer and longer, even 10 years, and the task models are more and more complicated, such as a mission designed for using the SSO to Probe the magnetic field, electric field and atmospheric density at the different altitude, so the sun-synchronous properties need to be strictly maintained by feasible low energy consumption strategy. Through the inclination, LTDN, and other orbit elements for integrated multi-passive control, the sun-synchronous properties drift can be kept within a minimum variation when the subtasks are targeting to different altitude in different period, which will not need extra fuel consumption. Firstly, the altitude and the time length of all sub-tasks should be defined, and then the offset of each orbit elements for the sequence of subtasks should be calculated, which will be optimized as an integrated mission. Finally, the optimal offset for each orbit elements will come out, and they can be accepted by the launch vehicle. The sun-synchronous properties are usually mainly characterized by LTDN, so the better sun-synchronous properties mean less variation of LTDN. In theory, the angular velocity of orbit plane precession should be strictly equal to the angular velocity of Earth revolution. In fact, the angular velocity of orbit plane precession has relationship with Earth gravity, atmospheric drag and the gravity of third body, such as the Sun and the Moon, etc. With the effect of all the perturbation, the LTDN will accelerate the drifting as parabolic curve. In each new subtask, the beginning LTDN is the final value of former subtask, so is the inclination and semi-major axis, etc. The LTDN drift curve is the function of SSO inclination at this subtask altitude, the real changing inclination and the beginning LTDN, etc. When all of the LTDN curves of subtasks are stitched together, the whole mission will get the variation of LTDN, and the process of optimization is the variation minimization by the least squares rule (LS). Through the iteration calculation and feedback, the system will gain the best multi-passive control offset. In order to reduce the calculation time, adaptive steps of variables are used, which can determine the convergence direction initially and get the final best multi-passive control offset quickly. subtasks are related to each other, so some subtasks with bad efficiency can be figured out by the multi-passive control system performance, and engineer can propose some necessary changes to the mission. Eventually, the mission requirements and project realization ability will be met. [View Full Paper]

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MARS ATMOSPHERIC ADAPTIVE ENTRY GUIDANCE BASED ON ON-BOARD TRAJECTORY PLANNED

Minwen Guo,* Xiangyu Huang,† Dayi Wang‡ and Maodeng Li§

An adaptive entry guidance is presented for Mars exploration lander with low lift-to-drag ratios, the limited control authority and large initial states bias. The law is developed based on on-board trajectory planned. Firstly, the nominal trajectory is designed which described by the downrange value and other states such as drag acceleration, altitude rate. Then to the large initial state bias, the nominal downrange value is modified on-board by weighing the landing accuracy, control authority and parachute deployment altitude. The most prominent advantage of this approach is that it can successfully correct altitude error and avoid the control saturation. Finally, simulation results illustrate the adaptive guidance law can effectively decrease the parachute deployment altitude and dynamic press error. [View Full Paper]

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ON-BOARD GUIDANCE LAW DESIGN OF ALL-ELECTRIC PROPULSION SATELLITE WITH MOMENTUM WHEEL CONTROL MOMENT CONSTRAINT

Min Wang,[*] Ran An,[†] Xingang Liang,[‡] Chuanhui Duan[§] and Qiang Li[**]

The whole orbital maneuver task is performed by Electric Propulsion System who affords low-thrust propulsion in All-electric Propulsion Satellite. In the low-thrust transfer trajectory optimum design methods, direct and indirect method can be used to get optimum solution. However, these methods are complicated to solve, large in calculation, poor adaptability to orbit error, and the results usually exceed the control moment constraint of Momentum Wheel. So they can only be used in the theoretical analysis and calculation, and can't be applied to the design of orbit transfer guidance law. On-board guidance law can reduce Ground-based monitoring system and personnel workload during 4 to 6 months of orbital transfer period, and enhance autonomy of All-electric propulsion satellite. Considering the computing power limitation of the on-board CPU, the design of guidance law based on Lyapunov optimal feedback control method is a reliable way. An on-board guidance law design method of all-electric propulsion satellite is proposed and the control moment constraint of Momentum Wheel has been considered. The guidance law is easy to implement on on-board computer. It has good adaptability to navigation or control errors during orbital transfer period and can meet the requirements of attitude control. The method is of great importance engineering meaning and provides reference for transfer trajectory design of All-electric propulsion satellite and Deep-space exploration satellite based on electric propulsion system. [View Full Paper]

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A VISION-AIDED REAL TIME NAVIGATION SCHEME FOR PINPOINT LANDING ON MARS

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Landing a spacecraft within 100 m of the predefined site is required in future mars exploration missions, which largely challenge the navigation performance. In this paper, a vision-aided real time navigation scheme, designed for pinpoint landing on mars, is proposed to meet the required precision. In the scenario, a map with multiple layers of different resolution of the landing area is generated by the mars orbiter before entry, descent and landing (EDL). The state estimation of the lander from the navigation filter is used to determine the scale difference between the descent image and the map to improve the efficiency and performance of image feature extraction. Then, the geometric relationship of the key-points in the image is analyzed based on dilution of precision (DoP), and a simple and efficient method was presented to select a few key-points those affect estimation accuracy most as the inputs of the navigation filter, which largely cut the time-cost of feature description and matching. To obtain the state update, the vision observations are tightly fused with the inertial measurements using an extended Kalman filter (EKF). Finally, the sequential images in the powered descent phase and the map of the landing area are simulated to validate the proposed navigation method. Simulation results show that the mean navigation errors at touchdown are 1.2 m for position, 0.125 m/s for velocity, and 0.082 degree for attitude.

Keywords: Mars landing; vision-aided; real time navigation. [View Full Paper]

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PULSE PROPORTIONAL GUIDANCE LAW FOR DEEP SPACE MPACT MISSION

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Deep Space Impact is an important way of asteroid exploration, of which a high precision guidance law is considered to be the key technology. The relative dynamic equation of the deep impact mission is derived. Then, a pulse proportional navigation guidance (PPNG) law based on the required LOS rate is developed accordingly. In contrast to the predictive guidance law, PPNG works without complex state estimation by filtering algorithm. Therefore, PPNG avoids the possibilities of long convergence time and poor estimation accuracy. Numerical simulations are presented to compare these two guidance laws. And semi-physical simulation system is built to verify the practicality of the proposed guidance law. Results of simulations show that although PPNG is of slightly lower impact precision than predictive guidance law, it can still meet the demand of the mission. And considering the consumption of velocity increment, PPNG works as well as predictive guidance law. These results show that the presented PPNG can be better utilized for practical applications. [View Full Paper]

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STUDY ON EVALUATION METHOD OF AUTONOMOUS MANEUVERING CAPABILITY OF SPACE VEHICLE

Lei Tian,[*] Ruijun Wang[†] and Peng Wan[‡]

The orbit transfer vehicle is a class of aircraft with autonomous maneuvering capabilities and undertakes tasks such as future space-based orbit services, space manipulation, and space resource allocation. In the stage of technical verification test, not only should a comprehensive evaluation of the spatial autonomous mobility capability be made, but also various indicators that affect the spatial mobility capability should be evaluated to provide a basis and reference for core technology research and capacity expansion. Based on the spatial autonomous maneuvering test task, this paper decomposes the spatial autonomy maneuvering capability and obtains various evaluation performance indicators. A step-by-step assessment strategy is adopted to perform "process assessment" and "target assessment" respectively. By means of multi-lap orbit determination, three-station joint measurement, GPS differential positioning, synchronous simulation and other means the relevant telemetry data and measurement data are obtained for evaluation of the spatial autonomous maneuverability. [View Full Paper]

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AN ASYNCHRONOUS INTEGRATED NAVIGATION METHOD BASED ON MARS AND PULSAR OBSERVATION

Ju Xue,[*] Hengnian Li,[†] Jun Duan[‡] and Yong Li[§]

Because of the long time and long distance, Mars exploration often has great time delay. X-ray pulsars, with high precision rotation period, were used to provide position, velocity and attitude information for autonomous navigation spacecraft. So the X-ray pulsar autonomous navigation technology has great development potential and strategic significance. A problem for X-ray pulsar navigation is that obtaining the same time of arrival (TOA) accuracy, different pulsars require different signal observation periods. However, in past studies, researchers have tended to ignore this problem. Thus, they assume the pulsars used for navigation have the same signal observation period. Ignoring these variations will greatly influence navigational accuracy. Therefore, for differing signal observation periods, we propose an asynchronous observation model for the process of X-ray pulsar navigation. In order to improve the accuracy of autonomous navigation and location at the end of Mars probe cruise terminal, combining with pulsar observation information and Mars observation information, this paper proposes an integrated navigation method based on asynchronous observation. The simulation results show that the integrated navigation method base on the asynchronous algorithms are superior to the synchronous algorithm. [View Full Paper]

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MINIMIZATION OF DISPLACEMENT DEVIATION FOR SPINNING, THRUSTING SPACECRAFT USING TWO-BURN SCHEME

LIANG Zhenhua,* LIAO Wenhe† and ZHANG Xiang‡

During axial thrusting of a spinning spacecraft, misalignment and center-of-mass offset can cause unwanted body-fixed torques which result in displacement deviation in the inertial space. A two-burn scheme is introduced to eliminate this deviation. Analytical solutions for the angular velocity, Euler angle, inertial velocity, and inertial displacement with nonzero initial conditions are given. The example is used in the numerical analysis, the simulation results show that the analytical solutions closely match numerical simulations accurately. Based on the analytical solutions, the effect of two-burn scheme is analyzed by varying burn and coast time, and the worst situation can be found which produce the maximum deviation. Also, the behavior of inserting additional revolutions during the initial burn and coast time is considered to find solutions that minimize the displacement deviation. The improved two-burn scheme realizes a significant decrease in the displacement deviation. This theory may be applied to onboard computations, maneuver analysis, and maneuver optimization. [View Full Paper]

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ROBUST CONTROL OF SPACE ROBOT WITH CONTROL TORQUES BOUNDED AFTER IMPACTED BY A CAPTURING TARGET BASED ON ENERGY THOUGHT

Mao FAN,* Xiao FENG,† Shan LU,‡ Yueyang HOU§ and Yinghong JIA**

The paper proposes an energy-based robust technique which is to stabilize the compound system and damp out joint velocities after capturing the target. Dynamics model for a 7 DOF space robot is first derived by using Kane's equation. Then, a modified adaptive sliding mode control algorithm with control torque bounded is proposed to track the desired trajectories. And the adaptive algorithm is applied to estimate the boundary of disturbance. In order to achieve good performance without chattering effect, a new signum function is presented in the controller., energy-based desired trajectories of joints velocity with control torques bounded are derived by using Lyapunov function. This energy-based Lyapunov function applies an energy-based way to eliminate target movement and stabilize space robot joints and minimize energy consumption of joints control torque. Saturation function is used to ensure that control torques are under the restriction. Uniformly ultimate boundedness is proved based on Lyapunov method. Finally, simulation results show the effect and stability of the proposed algorithm. [View Full Paper]

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IMAGE TERMINAL GUIDANCE BASED ON YOLO V2 FRAMEWORK

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The traditional image terminal guidance algorithm can't adapt to the change of target size well and poor in generalization ability. Recently the object detection algorithm develops rapidly in the support of deep learning, the YOLO v2 network got the best detection effect in the field of object detection in 2016. In this paper, we proposed a new approach for image terminal guidance based on YOLO v2 framework (short for G-YOLO). First, we get the training data through the Internet and experiments, then using improved clustering methods and experiments to determine the size of Anchor-box, to get more accuracy. Second, on the basis of trained network using Pascal-VOC dataset, we simplify the network structure by experimenting, to improve speed of detection obviously. Third, we use the multi-scale detection training to adapt to the drastic changes of the target size during terminal guidance. Experiment results show that the proposed method is robust to rapid changes of target size, and the accuracy and stability is superior to traditional methods. [View Full Paper]

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ASTRODYNAMICS WITH ARTIFICIAL INTELLIGENCE

Session Chairs:
Shuang Li
Davide Guzzetti

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GENERATION METHOD OF SMALL CELESTIAL BODIES DIGITAL TERRAIN MODEL BASED ON GEOMETRIC AND PHOTOMETRIC INFORMATION

LIU Xing-tan,[*] WU Yan-peng,[*] WU Fen-zhi,[*] Zheng Ran[*] and Liang Xiao[*]

In deep space exploration for small celestial bodies, one considerable concern is the navigation accuracy. Therefore, a comprehensive generation method of digital terrain model (DTM) is of significance. In order to realize the requirements of the detection task and give full play to the dual role of optical camera's observation and navigation, it is necessary to carry out research on asteroid DTM technology. By combing photogrammetry and photoclinometry methods, stereophotoclinometric (SPC) design is discussed; the ways to derive DTM with shape model are exhibited and, finally, errors that effects photoclinometry are analyzed. [View Full Paper]

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ARTIFICIAL INTELLIGENCE LOGIC CONTROL FRAMEWORK AND IMPLEMENTATION METHOD OF SATELLITE GNC SUBSYSTEM

Yu Ning,* Jingjing Liang† and Yu Zhang‡

In this paper, an artificial intelligence logic control framework of GNC subsystem is proposed. The machine learning method is used to realize satellite autonomous orbit implementation task. In this framework, the satellite is divided into logical control layer, structure selection layer and support algorithm layer. The logic control layer is the main content of this paper. If the target is not specified manually, the target tendency is established and the intelligent state transfer decision is made. The output value of the intelligent state transfer decision is the state that the system should have in the next step, which is the selection of some certain combination of the structure selection layer. The trend prediction module directly predicts the success probability of the final target after a one-step state hypothesis. The tree search method is used to combine the state transfer decision making module and the trend prediction module. The probability statistics of multiple branches are calculated, and the optimal branch is selected to form the final control sequence and output as the result. The algorithms mentioned above mainly use artificial neural network and Softmax regression, while the reinforcement learning being included in the training process. Random forest is used to predict and diagnose non-state key faults. The system functions are demonstrated through two examples. [View Full Paper]

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A CONCEPT OF A SWIMMING ROBOT FOR FUTURE EXTRATERRESTRIAL LIFE EXPLORATION

Hanqing Niu, Xiangyuan Zeng,[*] Jiangyu Guo, Yang Yu and Fei Zhang

In this paper a concept of a swimming robot is proposed inspired by the *Anomalocaris*, designed to explore the Europa's under-ice ocean where extraterrestrial life may exist. Anomalocaris is known as the largest ancient predator in the middle Cambrian. Unlike many sea fishes, Anomalocaris is considered as arthropod, which has a simpler body structure than vertebrate. It is likely to have an excellent swimming performance in the pristine ocean. A model for thrust calculation based on the reactive force generated by the fluid on its moving body is utilized in this work. First, the efficiency of two different edge contours are compared and some important relations representing the swimming performance are analyzed by considering key parameters, including but not limited to the wave number, the generated mean thrust and swimming patterns. In particular, an interesting relationship is revealed between the wave number and the swimming efficiency. An optimal wave number is obtained corresponding to the maximum efficiency. In addition, numerical simulations regarding the swimming pattern are performed to show its influence on the swimming performance. [View Full Paper]

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AI-AIDED PARAMETERS ESTIMATIONS FOR UNCOOPERATIVE SPACE TARGET WITH MEASUREMENTS FAILURES

Xianghao Hou* and Jianping Yuan†

Parameters estimations for uncooperative space targets are vital important for the On orbit servicing operations. With limited prior information of the uncooperative space targets, good parameters estimations will not only provide rich knowledge of the target but also figure out whether the uncooperative space target can be captured and controlled. Since the uncooperative targets are tumbling in space, only remote sensors (i.e. stereo camera and LIDAR) can be utilized to measure some useful information about them. However, under the uncertain space environment, the remote sensors sometimes cannot output reliable measurements and will lead to failures of the parameters estimations. This paper focuses on parameters estimations of an uncooperative space target with measurements failures. In this paper, a LIDAR device is used to obtain the relative pose between the target and the servicing satellite, and long-term measurements failures of the LIDAR is considered. To enhance the estimating accuracies and efficiencies, the dual vector quaternions (DVQ) are utilized to model the system kinematics and dynamics. By the novel DVQ modeling technique, both the translational and rotational parameters can be estimated in the same time. Also, by utilizing the dynamic models, the inertial parameters (ratios of the moments of inertia of the target, and the location of the center of mass) can also be estimated. In the beginning, a DVQ based extended Kalman filter is designed to estimate the parameters of the uncooperative space target when the measurements of the LIDAR are available. Then, to overcome the estimating failures caused by the faults of the LIDAR measurements, a neural network aided extended Kalman filter (NNEKF) is designed. In the designed NNEKF, a BP neural network is designed in the measurement update procedure when the measurements from the LIDAR are failed. By using the historical time propagations of the states and the Kalman gain as inputs together with the relative correct estimations of the states as outputs, the designed BP neural network is trained off-line firstly. Then, when the measurements of the LIDAR is available, the trained BP neural network is retrained by the results from the DVQ-EKF in each estimating step to enhance its online estimating accuracy. As soon as the measurements failures happen, the designed BP neural network will output the estimations of the parameters instead of the ones made by DVQ-EKF. When the measurements of the LIDAR are available again, the estimations of the designed BP neural network will be used to reset the DVQ-EKF, which will be used under available LIDAR measurements situations. By the proposed DVQ-NNEKF, the measurements update procedure can switch between the designed BP neural network and the EKF to enhance its accuracy due to the availabilities of the LIDAR measurements and mitigate the computational burden. Finally, the proposed DVQ-NNEKF is validated by mathematical simulations to show its robust performances.

[View Full Paper]

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MARS ENTRY TRAJECTORY ROBUST OPTIMIZATION BASED ON EVIDENCE UNDER EPISTEMIC UNCERTAINTY

Yuechen Huang,* Haiyang Li,† Xin Du‡ and Xiangyue He§

The epistemic uncertainties caused by lack of knowledge in atmosphere, aerodynamic coefficient and entry state make the entry process challenging, since they not only result in the deviation of preplanned trajectory, but also may lead to non-satisfaction of path constraints. In this paper, a robust epistemic uncertainty optimization (REUO) method based on evidence is proposed to solve the Mars entry trajectory optimization problem under epistemic uncertainty. The belief and plausibility from Dempster-Shafer theory of evidence are employed to quantify the evidence level of trajectory terminal deviation in REUO objective function. In addition, the maximal and minimal trajectory performances within each focal element (FE) are used to evaluate the evidence level. Therefore, the two-level nested robust optimization model is formulated. Besides, to solve the path constraint violation problem under uncertainties, the constraint design based on extreme case is considered in the robust optimization model. The random set theory is used to analyze the epistemic uncertainty propagation in stochastic entry dynamics. The original averaging discretization method (ADM) is modified to adapt to boundary points of the interval-based epistemic uncertainties and is used to discretize the uncertainty space into FEs with associated Basic Probability Assignments (BPAs). To improve the computational efficiency of the two-loop optimization resulted by the two-level nested optimization model, the polynomial chaos expansion (PCE) is employed into the inner-loop optimization to obtain the approximate analytic function of trajectory performance under uncertainties. Thereafter, the inner-loop optimization can be readily and rapidly solved. The REUO method is tested in a specific Mars entry mission. The simulation results show that the proposed method can identify the most robust solutions with optimal trajectory performance under epistemic uncertainties. [View Full Paper]

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PSEUDOLITE LAYOUT STRATEGY FOR BEIDOU SATELLITE NAVIGATION SYSTEM BASED ON MODIFIED DIFFERENTIAL EVOLUTION ALGORITHM

Zhipeng Chen,[*] Long Zhao,[†] Xiao Liu[‡] and Ye Tao[§]

According to the construction and development plan of Beidou satellite navigation system, Beidou III satellite navigation system is planned to be completed around 2020 and to provide services to the world. To improve reliability, availability and service accuracy of the system, and enable the system to provide users with high precision navigation, positioning and timing services in "Urban Canyon" and other special circumstances, it can be considered to establish space-based pseudolite augmentation system. Like the traditional satellite navigation system, the positioning accuracy of the pseudolite augmentation system is closely related to the geometric distribution of the pseudolites. Because of its strong global optimization capability, the differential evolution algorithm (DE) is used in this paper for completing the optimization of pseudolite layout strategy. The GDOP (Geometric Dilution of Precision) value of the pseudolite system is set to the value of the objective function. At the same time, aiming at the problem that if the basic differential evolution algorithm deals with the high-dimensional function, the convergence rate will be slowed down, the "social cognition part" of the particle swarm optimization algorithm (PSO) is introduced into the basic differential evolution algorithm, and then, a modified differential evolution algorithm is proposed. This algorithm firstly adds stochastic mutation operation to the basic differential evolution algorithm, to increase the diversity of the population and improve the search ability of the algorithm. At the same time, the mutation factor is dynamically adjusted so that the algorithm avoids premature convergence and has strong local search capabilities in the later period. In addition, the optimal individuals in the current population are added in the crossover operation step, and the convergence rate of the algorithm is improved. Simulation results show that compared with the basic differential evolution algorithm, the modified differential evolution algorithm has better optimization performance and convergence rate, which is helpful to find an optimal space-based pseudolite augmentation system networking layout strategy and enhance the positioning accuracy of the pseudolite augmentation system. [View Full Paper]

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THE FEASIBILITY STUDY OF CROSS STRAIT CHINESE COOPERATION IN ADVANCING PHAS (PRIVATE HUMAN ACCESS TO SPACE) COMMERCIAL AND TOURISM INDUSTRY

James Yu-Shan Liu*

In this paper we will propose a cross strait cooperation framework for Chinese of both sides to collaborate the possible commercial sub orbital or orbital flight incorporating the launch and carrier technology of China and the intelligent astronautics vehicle parts manufacturing and precision optical CMOS technology of Taiwan. The cross-strait consortium could design the following cooperation agenda. [View Full Paper]

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INTEGRATED GUIDANCE FOR MARS ENTRY AND POWERED DESCENT USING REINFORCEMENT LEARNING AND GAUSS PSEUDOSPECTRAL METHOD

Xiuqiang Jiang,[*] Roberto Furfaro[†] and Shuang Li[‡]

Traditional studies on Mars entry, descent, and landing (EDL) usually take a divide-and-conquer approach where each phase is investigated separately. This paper proposes a new approach to achieve integrated guidance for mid-lift high-mass human Mars entry and powered descent. The Gauss pseudospectral method is adopted to shape optimal entry trajectories and propellant-optimal powered descent guidance, respectively. According to the interaction between the entry trajectory and the propellant usage in the powered descent, reinforcement learning algorithm is employed to obtain the optimal integrated guidance. It is shown in this paper that appropriately integrating the working of the entry and powered descent guidance can bring great reduction in propellant consumption during high-mass Mars powered descent. Each of these two components and how they work together to reach the least propellant usage and pin-point landing are investigated in this paper. Numerical results are presented to demonstrate the effectiveness of the proposed method. [View Full Paper]

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NEW INTELLIGENT LATERAL GUIDANCE TECHNOLOGY BASED ON DEEP REINFORCEMENT LEARNING

Minqian Chang,* Lin Cheng† and Qingzhen Zhang‡

Aiming at the problem of lateral guidance in the reentry process of hypersonic vehicles, a lateral guidance method based on deep reinforcement learning is proposed. The traditional approach uses a pre-designed lateral corridor lead to excessive bank reversals, which brings a heavy burden for the attitude control system. The one/two-bank-reversal strategy performs poorly in guidance robustness. To solve the above problems, the Deep Q-Learning(DQN) algorithm in reinforcement learning is used in this study. Through the deep neural network for state awareness and the reinforcement learning algorithms for self-learning of the optimal reversal strategy, the reversal timing of the bank angle can be intelligently determined. This method solves the contradictory relationship between the times of reversal and the guidance accuracy, which can effectively improve the overall guidance accuracy and robustness. In the terms of longitudinal guidance, the least squares online model identification method is used to fit the implicit function relationship between the size of the bank angle weight and the predicted range, and the bank angle instruction in each guide period are solved by period-crossing correction. Using the parameters of CAV-H hypersonic vehicle for simulation, the results show that this method can not only effectively control the times of reversals, but also can maintain good guidance accuracy. [View Full Paper]

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A STUDY ON THE EFFECTS OF REUSABLE SUBORBITAL LAUNCH VEHICLE TRAJECTORY DYNAMICS ON THE NEURO-VESTIBULAR SYSTEM OF PASSENGER AND PILOT

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

From 2017 to 2018, many business activities are going on within the two most ambitious reusable suborbital launch vehicle (RSLV) developers Virgin Galactic and Blue Origin. Also, both Virgin Galactic's SpaceShipTwo (SS2) and Blue Origin's New Shepard System have very successful progresses in major test flights. All of these facts imply commercial suborbital scientific research and suborbital space tourism (SST) are approaching maturity. Since SST will open the excitement of traveling to suborbital space to thousands of tourists from general people, its effects on the pilots' and passengers' neuro-vestibular system has been investigated based on previous experience in both space and parabolic flights. Major difference between SST and space flight is the time duration of high-g acceleration, weightlessness and high-g deceleration flight phases. In SST, these three flight phases take place within about 12 minutes with each phase lasts for just a few minutes. Whilst in space flight, all phases take place in several days or even months. Therefore, sensorimotor disruption in eye movement, postural stability and motor coordination are very likely to happen in SST travelers. Even more, the SST pilots need to experience such cycle frequently during day-to-day commercial operations. A phenomenon of long term resonance to short term resonance might happen. Both authors of this study are not medical experts. But it is very important for non-medical expert to understand. Therefore, study and discussion on the effects along with strategies to mitigate and overcome these sensorimotor disruptions were presented. [View Full Paper]

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USER INTERFACES FOR LEARNING REDUNDANCY RESOLUTION IN HUMAN ROBOT INTERACTION

Weihui Liu,[*] Christian Emmerich,[†] Lizhi Zhang[‡] and Jochen Steil[§]

Redundant manipulator has good prospects for diverse and complex space operation tasks. However, teaching by demonstration of robot skills in the presence of redundancy is difficult and inefficient for non-expert users, especially with large and highly redundant manipulator, especially in complex confined scenarios. To master this task, two remote user interface systems are proposed and compared, which both comprise an input interface using mouse and keyboard, a visualization, an inverse kinematic solver and a machine learning component. The learner is used to generalize from a limited number of examples to a preferred redundancy resolution for a typical 7-DoF robot arm. The methods differ in the information that users can provide either through a novel approach to adjust Cartesian positions of certain key points on the robot's links and solve the inverse kinematics problem analytically, referred to as Keyposition interface. Or alternatively, users directly manipulate joint positions one-at-a-time along the manipulator and solve the inverse kinematics problem based on the pseudo-inverse Jacobian matrix, referred to as Nullspace interface. A non-expert user study is conducted to compare and the quality of the obtained redundancy resolution between Cartesian and Nullspace interfaces. The results show superior performance of the Keyposition approach in terms of teaching redundancy resolution to avoid collisions with the constraint environment based on users' intuitive knowledge. And the study is furthermore accompanied by in-depth interviews with domain experts for overall evaluation and further improvement. [View Full Paper]

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LOW-COST EPS FOR NANOSATELLITES CONSTELLATION OF BELT AND ROAD COUNTRIES

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In order to reinforce relationship between belt and road countries, spreading technology and space education for students, making space cooperation to build Nanosatellites constellation are proposed by the project presented in this paper. The preliminary estimated number of Nanosatellites necessary to cover these areas within short period of time is eight Nanosatellites, which will communicate with principle Ground Station (GS), other support GSs and redundant GSs. The proposed payload of the Nanosatellite is dedicated to track trajectories of transportations system, which may then be used to control the traffic jam along Belt and Road countries from ground-based stations by receiving the Automatic Identification System (AIS). The main focus of the presented research within this paper investigates the field relating to the Electrical Power Systems (EPS) for these Nanosatellites. Moreover, the design of the EPS is based on low cost Components Off-The-Shelf (COTS) component with the consideration of space environment and the acquired experience by the launched CubeSats. A simulation model of the Satellite EPS with the solar panel as main source and the battery storage as the secondary source was developed in MATLAB-SIMULINK. The close objective of this work is to test this new low-cost EPS hardware with the calculated parameters obtained from simulations. By simulation results and experimental tests, the effectiveness of the proposed control for the EPS is proven with environment changes in SSO of the nanosatellite constellation.

[View Full Paper]

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:
Bong Wie
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APPLICATION OF STAR TRACKERS FOR SATELLITE ANGULAR RATE ESTIMATION USING LOCAL ADAPTIVE THRESHOLDING AND PIV METHODS

Fahimeh Barzamini,* Shabnam Yazdani† and Jafar Roshanian‡

The main objective of this paper is application augmentation of star trackers as most accurate attitude determination devices to estimate spacecraft angular rates. In order to calculate spacecraft angular velocity from sequence of images in dynamic condition, two main issues have been addressed. First of all, image quality improvement through adaptive thresholding is considered. In this method a threshold level for image filtering against additional noise is used that will be most effective in improving the results of second part which is Particle Image Velocimetry (PIV) technique using Delaunay triangulation method to calculate spacecraft angular velocity. In order to use star tracker in dynamic conditions and in presence of angular rates, blurring of images will be a major challenge in detecting star centroids. In this paper, a locally adaptive thresholding method is applied that removes the image background noise by using local mean and mean deviation to improve the star tracker centroiding accuracy even in high slew rates. This method uses the image produced from integral sum of the main image as a reference for calculating the local mean, which does not include the computations of standard deviation existing in other local adaptation techniques and is independent of the window size which results in its accelerated implementation. Simulation results indicate that the performance of this algorithm is significantly high for noisy images, particularly when the signal to noise ratio is severely low. In the next step, after having denoised the images sufficiently, PIV method is applied to estimate the angular velocity. This method is based on tracking similar star patterns containing three or more star centroids in consecutive images without actually having to recognize the stars individually which is considered computationally laborious, so noise removal is an important issue affects in accuracy of satellite angular velocity estimation. The main issue of this paper is applying local adaptive thresholding algorithm on star tracker's images to use in the future methods. [View Full Paper]

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A CONTROL METHOD FOR DRAG-FREE SATELLITES BASED ON NOVEL KALMAN FILTER

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Drag-free technology is one of the key technologies of gravitational wave detection in space. The drag-free spacecraft consists of two parts, in which one is the inner test mass; the other is the outer spacecraft. In this paper, the relative dynamic models of spacecraft and test mass are established in the displacement mode, and the main disturbance sources are analyzed. In a hypothetical scenario, considering noise interference, the paper designs a Unscented Kalman Filter to estimate the relative state between the spacecraft and test mass, and the estimation are used for controller. Finally, simulation results are presented in order to verify the estimator can provide relative control estimation for drag-free control. [View Full Paper]

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A VARIABLE-UNIVERSE FUZZY PID CONTROLLER APPLIED FOR SATELLITE ATTITUDE MANEUVER

Peng Xu,* Zilong Zhang,* Ziyao Xu* and Jiandang Sun*

The dynamic performance optimization of satellite maneuver is a research hotspot in satellite attitude control. A fuzzy PID controller based on the variable-universe algorithm is presented in this paper. Firstly, based on the requirements of maneuver task, the deficiency of traditional single set PID parameter control is analyzed. Then, the mathematical characteristics of maneuver process is analyzed thus, a variable-universe algorithm whose variable-universe coefficient is adaptively adjusted by fuzzy logic is proposed. Finally, the control algorithm simulation using the variable-universe algorithm and the traditional algorithm is given respectively. The results show that the variable universe algorithm improves the dynamic performance of the maneuver tracking process effectively compared with the traditional one. [View Full Paper]

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INTEGRATED ATTITUDE CONTROL OF SOLAR POWER SATELLITE BASED ON ELECTRIC PROPULSION AND MOVING MASS SYSTEM

Ruinan Mu,* Shunan Wu,† Gianmarco Radice,‡ Zhigang Wu§ and Zhaohui Qi**

The integrated attitude control approach of a solar power satellite using electric propulsion and moving mass system is investigated in the paper. The coupling equations of the attitude motion and the moving mass motion are firstly established in the presence of environmental disturbances, such as the gravity gradient and the solar radiation pressure. By changing the location of the center of mass, the torque due to the solar radiation pressure can be utilized in the attitude control. The integrated control system is then designed in three steps. Firstly, a robust attitude controller, to perform attitude maneuvers of SPS, is proposed based on optimal LQR approach. Then the allocation algorithm for the electric propulsion and moving mass system is developed. A PD tracking controller, that drives the moving masses to generate the assigned SRP torque, is proposed. The moving mass system is investigated for the rolling-yaw motion and the pitching motion separately. Preliminary simulation results are obtained and the results demonstrate that the proposed integrated attitude control strategy with the moving mass system is more feasible and efficient. [View Full Paper]

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DISTRIBUTED COOPERATIVE VIBRATION CONTROL FOR THE SOLAR POWER SATELLITE

Enmei Wang,* Shunan Wu,† Xiangshuai Song,‡ Zhigang Wu§ and Yufei Liu**

To deal with the vibration problem of a solar power satellite (SPS), the distributed vibration control approach is presented in this paper. Taking large solar array of Abacus SPS as the research objective, the control unit (CU) is firstly defined for distributed controller design. The dynamic model of each CU is then developed, and the distributed cooperative controller is designed based on proportional differential (PD) control method. By designing communication of adjacent controllers of CUs, the distributed cooperative vibration control system of the whole SPS is therefore integrated. Finally, numerical simulations are presented, and the results demonstrate that distributed cooperative controllers can effectively achieve vibration suppression and has good fault tolerance.

[View Full Paper]

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MICROSATELLITE ATTITUDE CONTROL BASED ON NON-SINGULAR TERMINAL SLIDING MODE CONTROL

YANG Xinyan,* NI Shuyan,† LI Xiao‡ and LIAO Yurong§

This brief designs a non-singular terminal sliding mode controller for improving the anti-jamming performance of the microsatellite within the restraints of limited torque. The singularity problem in the terminal sliding mode control is solved by using a saturation function. It is proved that the designed controller can make the microsatellite converge to a neighborhood near the desired attitude within a finite time under the condition of limited torque. The expression of the convergence time is given. Finally, the simulation results show that the controller is robust to the external disturbances, which verifies the effectiveness of the controller. [View Full Paper]

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A MINIATURE ELECTROSPRAY THRUSTER FOR PRECISE ATTITUDE CONTROL OF A NANOSATELLITE

Chengyu Ma* and Charlie Ryan†

This paper introduces a miniature electrospray thruster, and investigates its feasibility of working as an attitude control actuator on CubeSat. The miniature thruster has a conically-shaped porous glass emitter, a porous nickel propellant reservoir and a 3D printed thruster casing. The propellant is passively fed through the porous structures using capillary action, resulting in a pressure-free and highly-compact thruster. The size of the thruster is approximately 1 x 1 x 2 cm with a total mass less than 10 g excluding a power control system. The thruster was tested in a vacuum chamber at the University of Southampton. Its thrust varied from 0.1 µN at ±2,600 V to 3 µN at ±2,900 V with a specific impulse higher than 6,800 s with a maximum power of 0.14 W. Based on the thruster specifications and test results, a hypothetical Earth-pointing 3 U CubeSat at a sun-synchronous orbit with an altitude of 500 km was used to analyse the attitude control and orbit maintenance performance of this miniature electrospray thruster. This analytical attitude and orbit control system uses a 16-thruster-configuration and a pulse-width-pulse-frequency modulation. Major orbital disturbances, including atmospheric drag, solar radiation pressure, magnetic field torques and gravity gradients, were considered in the analysis. This study suggests that the miniature electrospray thruster can enable precise attitude control with an accuracy of less than to 0.1 degree and orbit maintenance lifetime of about 6 years for a 3 U CubeSat at a 500 km altitude. [View Full Paper]

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THE ATTITUDE CONTROL SYSTEM OF ‘KUNPENG-1B’ SOUNDING ROCKET’S UPPER SERVICE PLATFORM

Peng Han,* Dong Gao,† Yanli Li‡ and Bonian Mao§

Sounding rocket is the only platform to explore the near space vertically. In order to create a stable and efficient platform for near space researches, the Attitude Control System (ACS) is added for the first time in the upper service platform of Chinese sounding rocket ‘Kunpeng-1B’. The composition, function, and attitude control algorithm of the ACS are introduced. The actuator is Cold Gas Thruster and the solenoid valves are used to control the outlet of gas to generate thrust. After separation, the upper service platform needs to complete control sequence of de-spinning, three-axis-stabilized, pitch maneuver and spinning-up with the help of ACS. During the de-spinning phase, the roll channel’s solenoid valves are actuated by the roll rate error through pseudo rate modulator (PSR). The active nutation control is implemented firstly in this phase. When the nutation angle exceeds the threshold, the pitch channel’s solenoid valves are enabled to generate lateral moment to prevent nutation angle divergence. During the three-axis-stabilized phase, the pitch, yaw, roll angles maintain at 60°, 90° and 0°, respectively. To increase the damping, both angular rate and angle error are introduced to PSR modulator. The decoupling control strategy of three-axis-stabilized control is that the roll channel has the highest priority. The pitch and yaw channel’s controllers are enabled only if the absolute value of roll angle reduces below 25°. The pitch maneuver phase begins when the upper service platform reaches the peak altitude. The pitch angle descends to -60° during this phase. During the spinning-up phase, the roll rate maintains at 180°/s for 2-dimensional space measurement. On 27th, Apr. 2016, ‘Kunpeng-1B’ sounding rocket equipped with the new ACS was launched successfully. The roll rate is 330°/s and the nutation angle is about 75° before ACS works. Even under this large perturbation condition, the ACS still completed all missions successfully. The telemetry data demonstrates the effectiveness and the robustness of the control algorithm. [View Full Paper]

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AERO-ASSIST TURNING STRATEGY FOR ROCKET LAUNCHING

Zheng QI,[*] Lin CHEN,[†] Meijing TAN[‡] and Lansong WANG[§]

Turning strategy is important in the launching of first stage of the rocket, during which aero-assist turning strategy could save more propellant for payloads. Turning progress could cost a significant energy loss caused by thrust component. Aero-assist turning progress could reduce the thruster energy loss by using aerodynamic lift. A turning strategy is given by using wings with small incidence angle for the rocket launching progress. Rocket drag force incurred by flying in atmosphere is analyzed, and energy loss caused by aero-assist turning is compared with the traditional launching. Wings and aerodynamic configuration are designed based on the traditional rocket can be used for the designing of horizon landing reusable launch vehicle, and the concept of RLV is given at the end of the paper. Simulation shows that aero-assist aerodynamic configuration could save more energy for rocket launching. [View Full Paper]

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AUTOPILOT DESIGN FOR AN AIRCRAFT WITH AERODYNAMIC SURFACES AND LATERAL THRUSTERS

Tian Dong,* Zhi-guo Song† and Chang-jian Zhao‡

Aircrafts with both aerodynamic surfaces and lateral thrusters have great advantages in dynamic performance. The key to enhance the autopilot is balancing the two actuators by specified control methods. In this paper, an autopilot is designed for an aircraft with both aerodynamic surface and lateral thrusters via the sliding mode control approach. In order to realize the optimization of the cooperation between actuators, the original MIMO autopilot system is converted into a dual-loop model. Specifically, the aerodynamic surfaces controlled loop is designed by the sliding mode control approach, which is considered as the inner loop. On this basis, the inner loop is considered as an object to be controlled with choiceness in the lateral thruster controlled loop, which is relatively the outer loop. Control parameters are designed after iteration, and numerical simulation has been done to evaluate the performance of this autopilot. Simulation results validate the improved response performance and robustness against uncertainties and disturbance of the autopilot. [View Full Paper]

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COMPLIANCE CONTROL FOR SPACE MANIPULATOR BASED ON IMPEDANCE CONTROL

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There may be a large contact force between end-effector and target when space manipulator implements contact tasks, due to the presence of control and measurement errors. An impedance control law is presented in this paper to control the end-effector behave compliantly. The proposed law establishes dynamic relationship between end-effector position of manipulator and contact force. Contact force and moment are fed back into the controller so that the end-effector performs the corresponding compliance movement. Simulations of a single rigid body are implemented firstly to verify the control law. However, the extension to a seven-DOF space manipulator is considered next and it is a domain of further investigations. [View Full Paper]

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APPLICATION OF A MODEL-FREE CONTROL TO THE MASS BODY ATTACHMENT SPACECRAFT

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Abstract: For the space assembly formed by the service spacecraft capturing the target spacecraft, considering the unknown quality characteristics of the target spacecraft and unknown combination dynamics model, the model-free data driving control method is introduced into the space assembly orbit and the field of attitude control, and a dynamic linearization "generic function" is proposed to characterize the excitation response relationship of space assemblies. Then a data drive controller is designed based on this "generic function". Because this controller does not rely on the dynamic model of the assembly, it can solve the control problem of space service spacecraft with complex dynamic, time-varying dynamic parameters, and strong dynamic coupling. In this paper, the designed controller is verified by digital simulation, which proves the effectiveness and accuracy of this method. [View Full Paper]

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SMOOTH FINITE-TIME COORDINATED ATTITUDE CONTROL FOR A SPACE ROBOT BASED ON ADAPTIVE MULTIVARIABLE DISTURBANCE COMPENSATION

Jinyuan Wei[*] and Jianping Yuan[†]

This work investigates a smooth finite-time coordinated attitude control scheme for the space robot with strong system nonlinearities, multiple input torques, coupled uncertainties and unknown disturbances. This paper reformulates the dynamic equations of a space robot by taking reaction wheels into account. An adaptive multivariable generalized super-twisting algorithm based on sliding mode disturbance observer is introduced to estimate the lumped disturbances with unknown bounds in finite time. Utilizing the estimation as feedforward compensation, a multivariable homogenous smooth twisting algorithm based on coordinated controller is designed to ensure the finite-time attitude tracking and generate a smooth input signal. Simulations are provided to demonstrate the effectiveness and robustness of the proposed method. [View Full Paper]

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TIME-VARYING STATE-SPACE MODEL IDENTIFICATION OF ON-ORBIT RIGID-FLEXIBLE COUPLING SPACECRAFT USING A PREDICTOR-BASED RECURSIVE SUBSPACE ALGORITHM

Zhiyu Ni,[*] Jinguo Liu,[†] Shunan Wu[‡] and Zhigang Wu[§]

This paper focuses on the recursive identification of the time-varying state-space model of the on-orbit rigid-flexible coupling spacecraft caused by structural configuration change, and a recursive predictor-based subspace identification (RPBSID) method is applied to implement the online identification of the system model recursively. Comparing with the classical subspace algorithms such as the time-varying eigensystem realization algorithm (TV-ERA), the RPBSID method does not need to construct the corresponding Hankel matrix for each time instant when solving the state variables, and thereby reducing the amounts of data in the identification process. Furthermore, an adaptive filter is applied in this recursive algorithm and thus the ability of noise resistance is also increased. In numerical simulations, the time-varying state-space model of the spacecraft is estimated by using the RPBSID and TV-ERA approaches, and the system responses with respect to the test inputs for the two methods are also compared. The computed results of the test responses illustrate that the RPBSID algorithm can be used to effectively identify the time-varying state-space model parameters of the rigid-flexible coupling spacecraft, and the corresponding computational efficiency of the algorithm is also better than that of the classical identification method. [View Full Paper]

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ROBUST ATTITUDE TRACKING CONTROL FOR SPACECRAFT WITH PRESCRIBED PERFORMANCE

Fuzhen Zhang,[*] Lei Jin,[†] Shijie Xu[‡] and Yingjie Li[§]

An inertia-free robust attitude control technique is addressed for the spacecraft in presence of inertia uncertainties and external disturbance. The pre-scribed performance can be achieved under the proposed control law. A transformed error quaternion dynamics is firstly established with the application of the Prescribed Performance Function (PPF). Based on the newly defined transformed system, a robust control law is derived without the prior information of the disturbance and the uncertainties, and even the inertial matrix is not required. It is proved that the original system states, quaternions and angular velocities, will achieve the asymptotic stability. The simulation results also verify the effectiveness of the proposed control law. [View Full Paper]

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NONLINEAR DISTURBANCE REJECTION OF NANO-SPACECRAFT ATTITUDE TRACKING CONTROL

Changmao Qin,[*] Qunhai Qiu[†] and Jianhua Wen[‡]

For the modern space science mission, application of nano-spacecraft becomes more and more widely, such as deep space exploration, low-orbit experiment mission, etc. The influence of external interference on nano-spacecraft is very obvious due to its small size. The ability of rejecting disturbance for attitude control is very important to complete some missions. It becomes a benchmark problem that how to resist unknown external disturbances and parametric uncertainty for attitude control of nano-spacecraft. It has been extensively studied for disturbance attenuation of nano-spacecraft. Active disturbance rejection control (ADRC) method has been a valid way to restrain external disturbances and uncertainties of parameter and does not rely on any information of disturbances, parametric perturbation. Through the simulation of UKube-1, an advanced nano-spacecraft, it illustrates the robustness of the proposed control method to reject unbounded disturbance and parametric uncertainty. It is shown that the control method of this Note demonstrates an improved control performance by comparing with conventional PID controller.

[View Full Paper]

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THE DESIGN, TEST AND ON-ORBIT APPLICATION OF A GIMBAL CONTROL SYSTEM FOR MINI-VARIABLE SPEED CONTROL MOMENT GYROSCOPE

ZHAO Lei,* WEI Wenshan,† DAI Yaping,‡ ZHAI Baichen,§ WU Jintao, ZHANG Jiyang†† and GUAN Xin‡‡**

The China's first mini-Variable Speed Control Moment Gyroscope (VSCMG) had been launched with Super View-1 in December 28, 2016, which signals successfully application of on-orbit. Here the paper focuses on design, test and on-orbit application of gimbal control system for mini-VSCMG. A Permanent Magnet Synchronous Motor(PMSM) and an absolute-inductosyn is employed to constitute a gimbal angular rate closed-loop control system, with which, high performance is obtained within the angular-rate ranged from 0.01~60 deg./s and the high speed stability is validated to be better than 0.005 deg./s. Besides, a high dynamic response of gimbal performance that above 50Hz is realized by a composite controller. Furthermore, a dual range current detection circuit has been used to improve the control stability of gimbal angular rate over 10%. Moreover, with this gimbal control system, a 20 degrees of attitude maneuvering is able to completed within 17 seconds while the stabilization of satellites is superior to 0.0001deg./s.

[View Full Paper]

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SPACECRAFT DRAG-FREE AND ATTITUDE CONTROL SYSTEM DESIGN WITH MODEL PREDICTIVE CONTROL

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The drag-free and attitude control system is one of the key subsystems to control the spacecraft attitude and the relative motion between the spacecraft and the test masses on board the LISA Pathfinder, which is used to demonstrate the two test masses can be putting into a pure gravitational free fall condition around the sensitive axis with a very high acceleration accuracy in the measurement bandwidth. This paper presents how the controllers could be designed and tuned with the model predictive control method. The linearized dynamics model is given and transformed into state space model, and the main disturbances is analysed briefly. After describing the objectives and the specifications of the drag-free and attitude control system, model predictive technique is used to solve the MIMO optimal control problem with constraints or design specifications in detail. Time-domain simulation test results and the power spectral density plots are presented and analyzed to evaluate performance of controllers. [View Full Paper]

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MODELING AND ACTIVE VARIABLE STIFFNESS COMPLIANCE CONTROL OF VARIABLE GEOMETRY TRUSS

Ya Deng*

As a deployable structure, variable geometry truss(VGT) has shown its great potential in space robot operation. With the basis of same middle point, a model of equivalent manipulator was proposed. Transfer equations from VGT to equivalent manipulator and vice versa. Considering the marked effect on base spacecraft when operating in space, compliance control law is used stabilize target spacecraft. What's more, taking the difference of target spacecraft into consideration, an active variable stiffness law was presented. Numerical simulations were established to verify the performance of methods, showing that the compliance control law could track the desired position and keep joint variables in reasonable range. And the active variable stiffness law can deal with different situations.

[View Full Paper]

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HYBRID CONTROL FOR RAPID SPACECRAFT ATTITUDE MANEUVERS

Zhili Hou,[*] Xueqian Wang,[†] Zhiheng Li,[‡] Bin Liang[§] and Simeng Huang[**]

A strong robust hybrid controller consisting of cascade-saturation controller and variable-structure controller is developed to rapidly maneuver the spacecraft attitude under various physical constraints. The cascade-saturation surface, which is a type of sliding mode surface, is firstly developed to guarantee the trajectory consistency between sliding mode surface and cascade-saturation controller. An on-off type of input is then designed to hold the system states near the sliding mode surface under the constraint of actuator saturation (torque and slew rate). The stability and rapidity of the proposed controller is proofed. Finally, numerical simulations are performed to verify the feasibility of the proposed controller. [View Full Paper]

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ATTITUDE REGULATING MECHANISM DESIGN AND ANALYSIS OF SPACE LARGE APERTURE DEPLOYABLE MEMBRANE OPTICAL PRIMARY MIRROR

Yan Wang,[*] Yuxuan Liu,[†] Hui Yang,[‡] Chunlong Wang[§] and Fengshuai Lu[**]

With the rapidly increasing demand of space exploration missions, the space optical imaging system with large aperture, high resolution and excellent stability will play an important role in exploration and observation. The camera aperture is larger, system controllability, ground launch, space folding and pose regulating are more difficult based on current technology. Conditional imaging system has a disadvantage of heavy mass and is hardly to realize large aperture. In order to solve the numerous technical problems of traditional reflective imaging system, high-resolution and lightweight membrane based diffraction optical imaging system is proved to be a new technological approach. An optical primary mirror and a supporting deployable mast of Membrane based diffraction optical imaging system can be folded at launch, which is unrestricted by the payload volume of a rocket and can adapt to different satellite bus. Based on the theory and architecture of diffraction optical imaging, this paper proposed an effective method of system design and analysis of space deployable membrane optical imaging mechanism aimed at large aperture, high resolution and greater aperture to height ratio. A new deployable imaging mechanism including articulated triangular truss mast and membrane optical primary mirror supported by the triangular masts was proposed. The applicability of Stewart parallel mechanism in attitude adjusting mechanism of the primary optical primary mirror was analyzed thoroughly according to constraint conditions including large aperture, short distance and small range of motion. A parameter evaluation method based on controllability and regulation was proposed, and the structural parameters of Stewart parallel mechanism were analyzed. The attitude adjustment mechanism was designed based on the Stewart parallel mechanism, and the motion characteristics were verified by ADAMS and MATLAB. [View Full Paper]

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ON-ORBIT IDENTIFICATION OF INERTIA PARAMETERS OF FLEXIBLE SPACECRAFT

Dongbo Meng* and Kun Zhai†

The paper proposes a two-step method for the inertia parameter identification of a flexible spacecraft. Simulation result show this method can get high accuracy results and is suitable for on-orbit identification of inertia parameters of flexible spacecraft. Different from the identification of inertia parameters of rigid spacecraft, the vibration of flexible spacecraft caused by the excitation torque will reduce the identification accuracy. This paper presents a two-step method to design the proper excitation which cause very little vibration by combining the optimal excitation with the input shaper. First, an optimal excitation is designed by minimizing a scalar variable calculated from the largest and smallest eigenvalue of the regression matrix instead of the condition number in the usual optimal excitation design method. Then the input shaper is designed to reduce the vibration based on the frequency and damping ratio calculated from the coupling dynamics equation of flexible spacecraft. Finally, the proper excitation is obtained by convolving the optimal excitation with the input shaper. Once we get the proper excitation, the recursive least-squares algorithm is used to identify the moment of inertia matrix. Simulation results show that the new method can yield high-accuracy identification results of inertia parameters and is suitable for on-orbit use. [View Full Paper]

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A METHOD FOR EVALUATING THE IMPACT OF SMALL ASYMMETRY ON THE SPACE LANDER'S ATTACK ANGLE UNDER CONDITIONS OF RESONANCE MOTION

Xingchuan Liu,[*] Danhe Chen,[†] V. V. Koryanov[‡] and Wenhe Liao[§]

In order for the ballistic lander to move stably in the planetary atmosphere, the lander needs to have a smaller slew angular velocity about the longitudinal axis, thus allowing the lander to have a smaller attack angle. Due to manufacturing and assembly errors, there is a small asymmetry in the space lander: the actual center of gravity of the lateral displacement, centrifugal moment of inertia, the lateral moment when attack angle and slip is zero, it changes the position of the dynamic balance axis. Literature shows that in presence of small asymmetries, longitudinal axis of the lander deviates significantly from the velocity vector, and under certain conditions, the device may lose the stability of the movement. there may be resonance to make the attack angle larger, or even lose the stability of the movement. This paper presents a method to estimate the small asymmetry of the attack angle of the lander in the resonant modes of motion and to design the method for use in the initial stage. The method allows the analysis of the values of the design parameters and the aerodynamic coefficients through their asymmetrical influence on the attack angle of the lander, which proves the necessary conditions for the maximum space attack angle of the lander. And the paper demonstrates the possibility of using the proposed technique to quickly evaluate the relative influence of various small asymmetries on the value of the spatial attack angle of the lander under resonant motion conditions by the case. [View Full Paper]

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ATTITUDE MOTION PATH PLANNING AT LAGRANGIAN PERIODIC ORBITS IN THE CIRCULAR RESTRICTED THREE BODY PROBLEM

Mo-yao Yu* and Ya-zhong Luo†

The attitude motion path for a rigid body in fully nonlinear reference orbits is planned for the restricted three body problem. Pseudospectral method and dynamic analysis on phase plane are employed to explore the method of path planning for the coupled attitude-orbit dynamic system. Compared with previous work, active expected factors are considered instead of passive natural motion and the divergence of pitch angle can be significantly reduced. Finally, the paper addresses the question of how the translational motions and the configuration of the satellite affect the planning results via a large set of calculations.

[View Full Paper]

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VELOCITY ESTIMATION FOR SPACECRAFT WITH IMMERSION AND INVARIANCE OBSERVERS

Qingqing Dang,[*] Haichao Gui[†] and Ming Xu[‡]

This paper investigates the control problem of the spacecraft with only position and attitude measurement via coupled liner velocity and angular velocity observers. In the first instance, the coupled six degrees of freedom dynamics of a single spacecraft described by dual numbers (quaternions) are established. Then, a velocity observer is designed utilizing the immersion and invariance(I&I) methodology. The cross terms caused by angular velocity are absorbed by the high-gain injection. This observer takes into account the gravity gradient torque, gravitational force, measurement noise. The convergence of the observer states and the boundedness of injection gain are analyzed theoretically by Lyapunov function, and the exponential stability of the observer is proved. Furthermore, a PD position and attitude tracking controller is designed. The asymptotic stability of the closed-loop system of this observer-controller cascade structure is analyzed. Finally, the simulations are demonstrated to show the effectiveness of the theoretical results.

[View Full Paper]

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DYNAMIC MANIPULABILITY OF SPACE MULTI-ARMED EQUILIBRIUM CAPTURE

LI Chen,* CHEN Shiyu† and YUAN Jianping‡

The dynamic model of space multi-armed robot with a captured object is presented under constraint including contact, friction, and internal forces. The mapping from base wrench and joint torques to the object acceleration, base acceleration and internal force is obtained. The free-flying, free-floating, and other space systems can be described by changing the base wrench terms, base acceleration terms and their associated mapping matrices. With given base acceleration and internal force, a one-to-one mapping between joint torques, with or without base wrench, and object acceleration is obtained. With this mapping, the dynamic manipulability measure of space multi-armed equilibrium capture is presented similar to the original definition. Numerical examples of different systems are shown and compared with ground conditions. [View Full Paper]

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STUDY ON THE STABILITY OPTIMIZATION CONTROL OF MARS ROVER WITH ACTIVE SUSPENSION IN UNSTRUCTURED ENVIRONMENT

Ling Tang,[*] Delun Li,[†] Tao Liu,[‡] Baofeng Yuan[§] and Shimin Wei[**]

The stability reflects the anti-overturning ability of the Mars rover in different terrain environments. The terrain of Mars, which is rugged, steep and covered with gravels, is a kind of typical unstructured environment. On Mars, the stability is an important performance for the safety of the rover. The rover with active suspension has redundant degrees of freedom, and its configuration can be changed to improve the terrain adaptability. In this paper, the stability optimization control of the Mars rover with active suspension in the unstructured environment with the method of changing the configuration of the rover is proposed. Firstly, the kinematics model of the Mars rover with active suspension in unstructured environment are established and perfected. Then, the analytic function of stability optimization target associated with the configuration of rover is derived. And the desired angles of the rover driving joints, which is the inverse solution of the analytic function solved with Interior Point Method, are obtained and controlled. Finally, the dynamics and control simulation platform of Mars rover is established by Adams and MATLAB/Simulink software to analyze and validate the effectiveness of the stability optimization control strategy. The results show that the established kinematics model can completely describe the motion of rover by in unstructured environment, compared with the simulation results, the calculated accuracy of kinematics model is higher than 96%, and the stability margin of rover in unstructured environment can be increased more than 23% through the proposed stability optimization control strategy. [View Full Paper]

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SPACE MISSION DESIGN AND OPTIMIZATION

Session Chairs:
Hexi Baoyin
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CAPABILITY OF BALLISTIC CAPTURE/ESCAPE IN EARTH–MOON AND PLUTO–CHARON MODELS

Zongfu Luo[*] and Yuedong Zhang[†]

Capabilities of gravitational acceleration and deceleration in Earth–Moon and Pluto–Charon systems are studied within the framework of planar circular restricted three-body problem (PCR3BP). This mechanism makes use of purely gravitational forces, and may occur in non-Keplerian regimes. A strong chaotic dynamics are involved in both gravity environments due to their high mass ratios in our solar system. Initial conditions defined over a fine computational grid are integrated forward and backward. This allows us to categorize orbits into different sets, including stable, unstable, primary-collisional, and secondary-collisional. Ballistic capture/escape orbits are generated by manipulating these sets. Case studies with different Jacobi constants are employed in the context of Earth and Pluto environments. Several indices, e.g., maximum/minimum Kepler energy with respect to primary or secondary, capture/escape Kepler energy with respect to primary-secondary barycenter and corresponding time-of-flight (TOF), are proposed to assess the performance of orbits. Capability of ballistic capture/escape are analyzed by using a wide class of parameters values (i.e., Jacobi constant, Kepler energy and TOF). Judicious capture/escape transfers by means of natural gravities are obtained. These provide a guideline for practical interest. A cross-comparison between two gravitational fields are performed in order to evaluate the role of the mass ratio. [View Full Paper]

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ORBIT MAINTENANCE OF CHANG'E-5T1 EARTH-MOON LIBRATION MISSION

LIU Lei* and LIU Yong†

This paper deals with the maintenance of CHANG'E-5T1 libration orbit, aimed at solving the issue of instability and the subsequent control difficulty of the Earth-Moon libration orbit. 'Circling-continuation' is proposed as a control method for the maintenance of the libration orbit, thus forcing the satellite to revolve around a libration point one by one to achieve the optimal control energy. Meanwhile, the control strategy is formulated via using the prediction and feedback of next maneuver. A combination of the control method and the strategy will result in an optimal control of libration orbit. Based on the pertinent research and the tracking conditions of China, the CHANG'E-5T1 L2 orbit need to be corrected twice, one during the 9th to 12th day and the other during the 24th to 27th day after injection of the libration orbit. The total velocity increment of the two maneuvers averages 10.4 m/s. The results are approximately the same as the data in the CHANG'E-5T1 mission and the flight control scheme derived from this research led to success of the first Earth-Moon libration mission of China, i.e., the only Earth-Moon libration flight after the American ARTEMIS mission. The research can be directly applied in stationkeeping of the relay satellite in the upcoming CHANG'E-4 mission and is expected to benefit the other libration missions. [View Full Paper]

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TRAJECTORY DESIGN FOR EXTENDED MISSION OF CIRCUMLUNAR RETURN AND REENTRY TEST

Zhanfeng Meng,[*] Shan Gao,[†] Zhong-Sheng Wang[‡] and Wenyan Zhou[§]

Due to the complete success of the primary mission of circumlunar return and reentry test, as well as the sufficient propellant remaining, it was decided to conduct the one-year extended mission. The flight phases and new types of trajectory of the extended mission were designed before the implementation of the primary mission. This paper introduces the different phases of the extended mission and the trajectory design method applied in achieving the mission goals under the mission-imposed constraints. [View Full Paper]

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MIDCOURSE CORRECTION METHOD OF THE REENTRY POINT FROM THE CIRCUMLUNAR FREE RETURN TRAJECTORY

CHEN Lidan,[*] LIU Yong,[†] LI Junfeng[‡] and ZHANG Lei[§]

A four-stage correction strategy is proposed to satisfy the atmosphere reentry constrains including reentry time, reentry height, velocity path angle and orbit inclination. The four stages are earth-moon lambert control, hyperbolic B-plane parameters of the moon, elliptical B-plane parameters of the earth and reentry point parameters corrections. Then, a landing point matching method is developed by adjusting the flight time of the whole mission to ensure that the nominal landing point be in the orbital plane on the reentry time. Simulation results based on Chang'e-5 Test Mission show that the method and the strategy are effective and applicable for engineering application. [View Full Paper]

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OPTIMIZATION OF TEI STRATEGY IN A LUNAR SAMPLE RETURN MISSION

Zhong-Sheng Wang,[*] Zhanfeng Meng[†] and Shan Gao[‡]

In a typical lunar sample return mission, one-impulse or two-impulse strategy can be adopted for the trans-Earth insertion maneuver. It is found in this study that the use of an engine with large magnitude thrust is necessary for one-impulse strategy, which however may lead to poor orbital control performance. It is proposed in the study that the one-impulse strategy be replaced by a two-impulse strategy, with about one-day time difference between the execution times of the two maneuvers. The paper first addresses the basic design procedure of one-impulse strategy, then an optimization procedure is introduced for the design of two-impulse strategy, with numerical examples for the purpose of illustration. Also discussed in the paper is a design procedure for three-impulse strategy to achieve Moon-to-Earth transfer. [View Full Paper]

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METHOD OF ON-ORBIT OPERATION MANAGEMENT FOR EARTH-MOON L2 LIBRATION POINT RELAY SATELLITE

Weitao TIE[*] and Shishui YU[*]

A relay satellite flying near earth-moon L2 libration point can provide relay communication between lunar lander/rover on the far side of the moon and TT&C station on the earth. The weak stability near the earth-moon L2 libration point requires control of station to maintain the relay satellite on orbit. Meanwhile, relay satellite on-orbit work needs to coordinate with flight control on the earth and exploration on the moon. In addition, certain astronomical phenomena, such as lunar occultation and earth/moon shadow, should be considered. Based on the characteristics of landing exploration on the far side of the moon, a method and mode of on-orbit operation management for earth-moon L2 libration point relay satellite is proposed. Based on earth-moon L2 libration point three-body dynamics and referring to the existing lunar exploration and flying around earth-moon L2 libration point experiment, processes and features of relay satellite on-orbit operation management are studied. Routine management, station keeping controls and special circumstances treatments are investigated. Special operation management modes to different types of orbit are also analyzed. The results are intended to provide support to earth-moon L2 libration point relay satellite on-orbit operation management and may also provide reference to mission design and operation management relevant to earth-moon L2 libration point. [View Full Paper]

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PSEUDO-STATE THEORY BASED ITERATIVE DESIGN METHOD FOR ACCURATE GRAVITY-ASSIST INTERPLANETARY TRAJECTORIES

Bin Yang[*,†] Hongwei Yang[*,†] and Shuang Li[*,†,‡]

A novel method based on the pseudostate technique is proposed in this paper to deal with the gravity-assist transfer trajectory. The whole trajectory is firstly divided into several flyby and transfer segments, and then the power gravity assist model, which is developed according to the pseudostate theory, is built to solve the accurate flyby trajectory under the three-body dynamics. Finally, the iterative patched technique is employed to splice the transfer and flyby segments. The use of these techniques ensures the transfer trajectory can accurately link the departure and target points, which will greatly reduce the difficulty of subsequent precise trajectory design. The Jupiter transfer trajectory with Venus, Earth or Mars gravity assist is designed by the proposed method. The results show that this method takes relatively small time cost to obtain the accurate transfer trajectory.

[View Full Paper]

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OPTIMIZATION ALGORITHM FOR INTERPLANETARY TRANSFER TRAJECTORIES OF SOLAR SAILCRAFT BASED ON DEEP REINFORCEMENT LEARNING

Chengyang Zhou,[*] Lin Cheng,[†]
Qingzhen Zhang[‡] and Ke Fang[§]

This paper studies the optimization problem of transfer trajectories for solar sailcraft based on deep reinforcement learning (DRL). Firstly, the orbital dynamic model of an ideal solar sailcraft is established and the control angles at discrete time points are used as design variable, which avoids the guessing for initial value of covariables without physical significance. By this way, the optimization problem is transformed into nonlinear programming (NLP) problem. On this basis, the Markov model of solar sailcraft is established, and the reward function is designed according to objective function and constraints. Combining deep learning and stochastic policy gradient reinforcement learning, A3C (Asynchronous Advantage Actor-Critic) algorithm is implemented in the framework of Python+Tensorflow, and the transfer trajectories for solar sailcraft from geosynchronous orbit to Mars synchronous orbit is simulated to verify effectiveness of the algorithm. The simulation results show that the algorithm converges quickly, and the controller trained for 30000 episodes can meet the terminal constraints and has good real-time performance. The results successfully verify the effectiveness of deep reinforcement learning in solving optimization problem for interplanetary transfer trajectories of solar sailcraft. [View Full Paper]

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DISCUSSIONS ON GUIDELINES OF INTERPLANETARY GRAVITY-ASSIST TRAJECTORY OPTIMAL DESIGN

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Yi Rong,§ ZhuSheng Liu** and HaiYang Zhu††

Celestial gravity-assist technology can achieve a wide range of velocity change without consuming spacecraft's own energy, and this is regarded as one of the most effective orbital maneuvering methods in deep space exploration trajectory design. One major difficulty in optimal design of gravity-assist trajectory is to determine the sequence and applying time of celestial gravity-assists and additional maneuverings. So far, there hasn't been any effective method that can generally solve a gravity-assist problem or make sure to find a global optimal solution. A generalized optimal trajectory design guideline is presented and discussed in this article. For an interplanetary flight mission with specified departure condition and target, this design guideline is able to find out an optimal energy flight plan. This guideline can be used not only in optimal trajectory design inside Solar System but also in any celestial systems. [View Full Paper]

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A PRELIMINARY RESEARCH ON MARS ROVER MISSION PLANNING USING JSHOP PLANNER

Zeguo Wang,[*] Yujia Sun[†] and Cong Zhang[‡]

A preliminary research on mission planning of a Mars rover is presented using JSHOP planner. Autonomous mission planning is particularly required for the Mars rover due to the communication delay and window constraint between Mars and Earth. A tool named JSHOP (Java implementation of Simple Hierarchical Ordered Planner) is used in our preliminary research for Mars rover autonomous mission planning. JSHOP is a domain-independent planning system based on Hierarchical Task Network (HTN) planning. This planner is able to decompose higher level tasks into subtasks and also produce a sequence of actions to finish subtasks. In our design, the main mission for the rover is to autonomously take photos of two objects, and the rover could complete this mission by different activities: take a photo, charge, and move. Each activity could be implemented only if the power constraint is satisfied. These activities and tasks are described with PDDL language, so that JSHOP could search for a suitable sequence of activities to complete the main mission. Finally, simulation results illustrate that this method could autonomously achieve the main goal of the mission and generate reasonable sequence of activities.

[View Full Paper]

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PRACTICAL MISSION DESIGN FOR MARS TRAJECTORY OPTIMIZATION BASED ON THE EPHEMERIS MODEL AND FULL PERTURBATION SYSTEM

Mohammadreza Saghamanesh[*] and Hexi Baoyin[†]

This paper implements a practical Mars mission design to determine fuel-optimal low-thrust trajectories via a hybrid optimization algorithm. This mission design comprises a variety of space scenarios analysis and design problems. The primary purpose of this paper is to determine the impact of different scenarios on the final spacecraft mass in a practical space environment. In the first step, we determine a simplified common two-body scenario without any perturbation. The results of this scenario show that the computational process and final spacecraft mass are more efficient than existing solutions under the same conditions. Subsequently, the low-thrust optimal-control framework is modeled based on four dynamic equations models with the ephemeris model, complex constraints, and full perturbation system. This work optimizes eight practical scenario types, which comprise of a variety of the perturbations as uncertainties and the propulsion systems, and a set of the optimal hyperbolic excess velocity vectors, using multidisciplinary design optimization approach. The interaction of the optimal hyperbolic launch excess velocity vector with the low-thrust propulsions requirements is investigated. As a result, in a practical space environment, the perturbations can potentially cause considerable deviations on the spacecraft trajectory. In addition, the launch window analysis in order to find optimal escape date is examined. The hybrid method including a robust homotopic approach combined with the particle swarm optimization is implemented to overcome convergence challenges via the combination of some efficient techniques. The motivation behind of the optimization method results in the more efficient solutions with high-accuracy in comparison with existing solutions. [View Full Paper]

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STRATEGY OPTIMIZATION AND ANALYSIS OF SAFE MARS ORBIT INSERTION*

Jianjun Feng,† Zhiyuan Zhou, Qinghua Zhu and Gang Liu

Mars orbit insertion determines the success or not of Mars probe mission directly. Mars explorer should have the ability of full independent and highly reliability. The Mars explorer should design secondary orbit insertion strategy in short notice and carry out the strategy autonomously in case that some failures interrupt the control during Mars orbit insertion stage.

At present, in order to obtain the optimal fuel or other optimal solutions to meet a specific performance metrics, Pontryagin maximum principle is widely used in solving the problem of orbit insertion strategy optimization. However, the problem of Mars orbit insertion has the feature of strong nonlinear and multi-constraints, and Pontryagin maximum principle is sensitive to initial values, and gets into local minimum case usually, therefore, it is necessary to study and propose a more general, more reliable method to solve the problem of capture braking.

To solve the problems above, we propose the strategy optimization of safe Mars orbit insertion. Firstly, we design a safe control interval based on a comprehensive analysis of the multiple constraints during capture braking phase. Secondly, we propose a weighted performance index after taking into account of braking time and attitude control, and utilize nonlinear programming algorithm to search the control parameters of global optimization. This method overcomes the two problems of Pontryagin maximum principle which mentioned above. However, nonlinear programming algorithm has a problem that the process of finding result costs too much time to meet the demand of onboard computer. We bring forward a secondary orbit insertion strategy based on Newton iteration according to the failure of attitude and orbit control system to ensure the safety of autonomous capture control. If there are some failures in the process of Mars orbit insertion, onboard computer will calculate orbit insertion strategy using Newton iteration in less than 2 minutes. It is proved that the scheme can be used as the Mars capture braking autonomous security control strategy to improve the safety and reliability of Mars orbit insertion. [View Full Paper]

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SPACE FLYAROUND AND IN-ORBIT INSPECTION COUPLED CONTROL METHOD USING DUAL NUMBERS

**Lijun Zhang,[*] Ming Wang,[†] Jianlong Song,[‡]
Shuai Liu,[§] Yi Lu[**] and Hengnian Li[††]**

In this paper, both the proportional derivative feedback control and variable-structure sliding mode control methods based on dual number are proposed to design the space flyaround and on-orbit inspection missions. The dual-number-based spacecraft kinematics and dynamics models are formulated. The integrated translational and rotational motions can be described in one compact expression, and the mutual coupling effect can be considered. The space flyaround and on-orbit inspection mission model based on dual number is derived. Both the proportional derivative feedback control and variable-structure sliding mode control laws are designed using dual number. Simulation results indicate that both the proposed controllers can provide the high-precision control for relative position and attitude and the variable-structure sliding mode controller has relatively more advantages. [View Full Paper]

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TRAJECTORY DESIGN FOR KUIPER BELT MISSION USING MULTIPLE GRAVITY ASSISTS

Boqin Hu,[*] Dong Qiao,[†] Xiangyu Li[‡] and Qi Chen[§]

The Kuiper belt is a circumstellar disc in the outer Solar System, which consists mainly of small bodies or remnants originated from the beginning of the formation of the Solar System. While many asteroids are composed primarily of rocks and metals, most Kuiper belt objects are largely composed of frozen volatiles. These ancient materials could provide insights into the early history of the Solar System. In this study, a series of trajectories are designed for targets of Kuiper Belt missions using multiple gravity assists, departing from Earth between 2018 and 2050 based on the traditional flyby mission architecture. For fast missions, planetary gravity-assisted model associated with the differential evolution algorithm is used to design the trajectories to targets. For time-free exploration missions, based on the multiple gravity-assisted model and the global hybrid optimization algorithm, the multiple gravity-assisted trajectories to the targets of Kuiper belt missions are designed. The results of this paper can provide references to the trajectory design for Kuiper belt exploration in the future. [View Full Paper]

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LOW-ENERGY LOW-THRUST ORBIT DESIGN AND OPTIMIZATION IN MULTI-BODY GRAVITATIONAL FIELD

Yi Lu,[*] Chaofei Xu,[†] Wei Liu,[‡] Lijun Zhang,[§] Hengnian Li[**] and Xiyun Hou[††]

The design and optimization methods for low-energy low-thrust transfer orbit in multi-body gravitational field have been studied in this paper. The methods have been applied to the example of the transfer orbit between the parking orbits around Jovian moons. The "Halo-like Section" has been proposed, and the manifolds were simply parameterized and patched by the multi-body Lambert algorithm based on collocation method. Then using the global optimization algorithm, the deferential evolution (DE) method, a preliminary optimization result is obtained with minimum fuel consumption. The low-thrust transfer orbits are designed and optimized by the homotopic method in multi-body gravitational field and the multi-circle transfer orbit design method with fixed perigee height. The results show that the low-energy low-thrust transfer orbit with minimum fuel consumption could be effectively computed by the proposed methods. The methods could also be applied to the design and optimization of the low-energy low-thrust transfer orbit between other celestial bodies. [View Full Paper]

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OPTIMAL LANDING SITE SELECTION FOR PLANETARY LANDING USING MULTILEVEL OPTIMIZATION

Xu Liu,[*] Xiuqiang Jiang,[†] Youfeng Wang[‡] and Shuang Li[§]

Reliable hazard detection and landing site selection is a key technique to enable a pin-point landing for planetary missions. In this paper, multilevel optimization strategy is newly employed to deal with the landing site selection problem. This method transcribes the landing site selection process with constraints into a series of easier optimization sub-problems, which are then rapidly solved according to a predetermined sequence. In this algorithm, the landing site selection problem is deconstructed into three optimization sub-problems with restrictions: 1) determine flat areas with constraints of hazard terrain and mapping error of digital elevation model; 2) optimize candidate safe landing zones with constraint of fuel consumption; 3) optimize terminal landing site with constraints of slope, roughness and minimum landing diameter and control error. During optimization procedures, three optimizing indexes based on different constraints are defined to reduce the safe area gradually and the optimal landing site is finally detected. Furthermore, a derivative based hazard detection algorithm is also proposed to detect the flat area in the first sub-problem without identifying types of obstacles, which is different from the traditional detection methods. Finally, the numerical simulation is performed based on a DEM obtained by Chang'e-3. It proves the feasibility and validity of multilevel optimization strategy for landing site selection problem. [View Full Paper]

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AUTONOMOUS TRAJECTORY REPLANNING FOR LAUNCH VEHICLES WITH PROPULSION SUBSYSTEM FAILURE

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This paper presents an autonomous trajectory replanning algorithm for launch vehicles in propulsion anomaly situations. The basic objective function for offline reference trajectory optimization is to minimize the fuel consumption. However, in anomaly situations, the online planning objective is to guide the vehicle to a safety orbit closest to the target orbit by exhausting fuel. First, we give the engine failure time and thrust loss, and replan the trajectory for vehicle to inject the original orbit or a specific safety orbit. For the case of insufficient carrying capacity, this paper analyses the impact of orbit inclination and perigee altitude on the safety orbit. The terminal condition, injection orbit elements, can be transformed into position and velocity vectors via the strong nonlinear transformation, which is a challenge to numerical optimization algorithms. The adaptive collocation method by using the homotopy strategy is adopted for this multiple phase optimization to replan the rescue trajectory and its safety orbit. Simulation results indicate that the proposed adaptive collocation method has sufficient capability to handle the trajectory replanning problem. Especially for the unknown orbit trajectory replanning problem, this direct numerical optimization method can find the optimal safety orbit according to the analysis of orbit elements characteristics, and it can reduce the loss caused by rocket launching failure. [View Full Paper]

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MISSION RESCHEDULING FOR GEO ACTIVE DEBRIS REMOVAL

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In this paper, the rescheduling problem of debris removal in a coplanar GEO orbit is studied. The minimum-cost, two-impulse phasing maneuver is used for each rendezvous. Specifically, the SSc is conducting Active Debris Removal mission on schedule, and the remaining mission sequence is known. Suddenly, the users demand to insert new targets in emergency. A new mission sequence with new targets and un-completed targets is required. The goal of the rescheduling is to work out such a new scheme for the SSc, minimizing the total rendezvous cost, as well as designing the rendezvous trajectories. The reschedule model and solution algorithm are developed. Numerical simulations are carried out to demonstrate the effectiveness of the model and rescheduling method.

[View Full Paper]

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RENDEZVOUS TRAJECTORY OPTIMIZATION OF SPACE DEBRIS AFTER COLLISION

Sijia Hao,[*] Yasheng Zhang[†] and Lu Jia[‡]

For the space robots rendezvous with the space debris which classical orbit elements changes after collision, an optimization algorithm for transfer trajectory of multi-pulse rendezvous is proposed based on Gray Wolf Optimization. This method adjusts the transfer trajectory continuously through the optimization model for multi-pulse rendezvous trajectories, that based on the perception of the change of the classical orbit elements of the space debris orbit. To make the space robots rendezvous with space debris by least-energy transfer trajectory. Simulation results show that the proposed method can still make space robots rendezvous with space debris which classical orbit elements changes. The method can be used to remove space debris and recycle debris. [View Full Paper]

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MANEUVER PLANNING OF GEOSTATIONARY SATELLITES OPERATIONS USING MEAN ORBITAL ELEMENTS

Hong-Xin Shen,[*] Zheng-Zhong Kuai,[†] Tian-Jiao Zhang[‡] and Heng-Nian Li[§]

Mean orbital elements can be used for monitoring the satellite's long-term behavior and for maneuver planning. Dealing with mean orbital elements has the advantage that short period oscillations are not perceived. Attention has focused mainly on the mean orbital elements of low Earth orbits. In this paper method for the propagation of mean orbital elements at geostationary orbits is presented. The propagation algorithm introduces the effects of aspherical gravity, lunar and solar third-body attraction, and solar radiation pressure perturbations, all of which are separated into short-period terms, long-period terms, and secular terms. The long-period and secular perturbations provide equations for propagating the elements of mean orbit motion. Then, the maneuver planning problem is formulated as an optimization problem with boundary constraints, based on the mean motion dynamics of a geostationary satellite affected by perturbations. Simulation results show the feasibility of the control task on a geostationary satellite, and the accuracy of the mean orbital elements is thus evaluated through the application of the algorithm for determination the motion of geostationary satellite. [View Full Paper]

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STABILITY OF QUASI-SATELLITE ORBITS AROUND PHOBOS IN PLANAR CIRCULAR RESTRICTED THREE-BODY PROBLEM

WU Xiaojie[*] and XU Shijie[†]

A mission to Phobos, the Martian moon, is an appealing researching subject for both scientists and engineers. Though traditional Keplerian orbits are impossible for Phobos mission, quasi-satellite orbit has been proved to be stable if the initial conditions are appropriate. In this paper, quasi-satellite orbits around Phobos in Planar Circular Restricted Three-Body Problem is addressed. The stable ranges of the initial state variables of quasi-satellite orbits are studied by employing Poincaré's surface of section. Periodic quasi-satellite orbits are explored in this paper and the initial conditions of periodic quasi-satellite orbits are computed and provided. Based on those results, a method to determine a periodic quasi-satellite orbit by choosing a Jacobi constant and iterating KAM rings on Poincaré map is introduced to assist engineers in orbital design. With this method, family of periodic orbits are depicted to provide readers an intuitive comprehension to the periodic quasi-satellite orbit in this paper. [View Full Paper]

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OPTIMIZATION OF LOW-THRUST MULTI-REVOLUTION TRANSFERS BY SYMPLECTIC ALGORITHM

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Low-thrust transfer trajectories optimization has been considered a challenging optimal problem in the past decades, especially for multi-revolution cases. In this paper, a high-precision and efficient algorithm of low-thrust multi-revolution transfer optimization is developed. The optimal orbital transfer problem is posed as a constrained nonlinear optimal control problem. With the help of quasilinearization techniques, the nonlinear optimal control problem is converted to a series of constraint linear-quadratic optimal control problems. Then, based on the parametric variational principle and complementary conditions, the converted problem is transformed into a standard linear complementary problem which can be solved easily. The modified equinoctial elements are chosen to describe the motion of spacecraft for its convenience of expressing the phase propagation as well as non-singularity. A nominal trajectory is given to accelerate the convergence process of the optimal control problem. Numerical examples show that the proposed method possesses high accuracy and efficiency. [View Full Paper]

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END-OF-LIFE DISPOSAL MECHANISM SYSTEM DESIGN AND ANALYZE FOR HIGH ALTITUDE LEO SATELLITES

Hamed Ahmadloo[*] and Jingrui Zhang[†]

Highest number of operational satellites in LEO are concentrated in altitude range of 1300 to 1500 km and the current existing disposal mechanisms like drag augmentation methods and chemical propulsion systems for the end of life (EOL) scenario are not suitable enough regarding to required high amount of propellant and lack of sufficient air molecules for generating drag force, respectively. This paper will address a combined solution which can guarantee complete de-orbiting of the satellite at the end of the mission with higher efficiency than other individual de-orbiting systems and this de-orbiting subsystem can comply with current 25 years' limitation for after mission in-orbit time for any satellite. General system design and orbital numerical simulations for different cases has been presented to prove the feasibility of practical usage of this system.

[View Full Paper]

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LOCATION-ROUTING PROBLEM FOR GEOSYNCHRONOUS SATELLITES REFUELING

ZHANG Tian-Jiao,* SHEN Hong-Xin,† KUAI Zheng-Zhong,‡
LI Heng-Nian§ and YANG Yi-Kang**

This paper addresses the scheduling problem for refueling multiple geosynchronous (GEO) satellites. The problem is defined by a set of potential fuel tanker locations, a homogeneous fleet of servicing vehicles with limited capacities, and a set of fuel-deficient GEO satellites with known fuel demands. The objective is to open a subset of fuel tankers, to assign GEO satellites to these tankers and to design vehicle routes, in order to minimize the total mission costs. To achieve an economical refueling strategy, the fuel tanker location, satellite assignment and routing decisions are required to determined simultaneously. It is shown that this problem can be formulated as a location-routing problem (LRP). The proposed solving method is an ant colony optimization (ACO) metaheuristic, searching within two solution space: giant tours and true LRP solutions. Giant tours are then evaluated via a splitting procedure. The computational results indicate that the proposed methodology can optimally determine both the distribution of fuel tankers and the vehicle routes on the instances with a large number of GEO targets. [View Full Paper]

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SPACE-BASED MULTI-SENSOR MULTI-TARGET TRACKING FOR GEOSYNCHRONOUS SPACE OBJECTS

Han Cai,[*] Yang Yang,[†] Steve Gehly[‡] and Kefei Zhang[§]

This study develops a space-based multi-sensor multi-target tracking (MSMTT) strategy for geosynchronous space object (GEO) catalog maintenance. Compared with traditional ground-based approaches, the space-based sensors have better detection capability because they are rarely restricted by weather conditions and the day-night gap. Two space-based sensor networks based on geosynchronous transfer orbit and Sun synchronous orbit are investigated, and two hybrid sensor networks using both space and ground based sensors are proposed as a complementary approach. The expression of the Rényi divergence for δ-Generalized Labeled Multi-Bernoulli densities is derived and utilized as the reward function for sensor management. The proposed MSMTT method is formulated in the framework of the Labeled Multi-Bernoulli filter in conjunction with the information theoretic sensor management which assigns sensor tasks by maximizing the information gain. The proposed method is validated by two case studies, involving large scale GEO objects tracking and dim GEO objects tracking. Results indicate the better performance of the spaced-based and hybrid sensor network compared with the ground-based approach in terms of state and cardinality estimation, and the Rényi divergence achieves similar accuracy compared to the commonly used Cauchy-Schwarz divergence. Further, the GTO sensor network is more effective for dim GEO object tracking. [View Full Paper]

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MODIFIED FOURIER SERIES METHOD FOR PLANAR SHAPE-BASED DESIGN OF LOW-THRUST RENDEZVOUS TRAJECTORY

W.M. Zhou,* H.Y. Li,† Hua Wang,‡ D.T. Yu§ and X.C. Li**

The shape-based trajectory design method based on the Fourier series has gained more attention in recent times because of its high efficiency and adaptability. However, poor initial estimates of the optimal trajectory shape and deficiencies in the chosen state variables cause less optimal results for the high-eccentricity orbit transfer. Thus, this paper proposes a modified Fourier series method to overcome these flaws. First, planar pseudo-equinoctial elements are introduced into the scheme of the original Fourier series method, and a new initial-shape production strategy of a Fourier series for the circle-to-circle rendezvous trajectory is proposed. Then, the average angular velocity is introduced as an index to analyze the feasible regions of different methods. Finally, the circle-to-ellipse rendezvous trajectory is designed using the modified Fourier series method. For comparison, the results of the multi-impulse Lambert method, pseudo-spectral method, and traditional Fourier series method are also reviewed in this paper. The results prove that the modified method can design the planar circle-to-circle and circle-to-ellipse rendezvous trajectories more effectively and obtain velocity increments that are close to the optimal results. [View Full Paper]

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A TASK ALLOCATION AND COLLABORATION METHOD WITH APPLICATION TO AGENT CLUSTER OF REMOTE-SENSING SATELLITE

Bin Du,[*] Shuang Li,[†] Xiaohui Wang[‡] and Hongfei Wang[§]

To overcome the problems of inflexible interactive mode, low negotiation efficiency and poor dynamic responsiveness of traditional satellites cooperation mechanism, novel autonomous satellites collaboration methodologies should be investigated. This paper proposed a multi-dimensional and multi-Agent system (MDMAS) cooperation model. First, dense point targets are pre-processed using task clustering. Second, a multi-dimensional and multi-Agent interactive cooperation model for remote sensing satellite is constructed, which assigns tasks by use of the Contract Network Protocol (CNP). On this basis, the bid method for point targets and clustering task sets is addressed. Finally, a bid evaluation approach based on multi-index weighting rules is developed to improve the efficiency of task allocation. Simulation results show that the new model can effectively solve the problem of task assignment. [View Full Paper]

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INTEGRATED BALLISTIC DESIGN OF SMALL-LIFT LAUNCH VEHICLE USING HIERARCHICAL OPTIMIZATION

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An integrated ballistic design strategy using hierarchical optimization for small-lift launch vehicle is studied in this paper. This strategy is accomplished by application of state of art rocket modelling techniques combined with hierarchical optimization. Distinguished from classical ballistic design strategy which highly relies on the large-scale computation to search a proper starting point, this hierarchical optimization strategy focuses on the relations of design variables in different temporal and spatial processes and generates a legitimate initial starting point from the mathematical aspect. Thus, the final optimized variables will be acquired within the neighborhood of the initial parameter set through the global optimization in the upper level. A simulation based the Electron rocket is executed to demonstrate the feasibility and effectiveness of this hierarchical integrated design strategy. Grounded with reasonable engineering methodology, such a design strategy can be extended to more complex ballistic design problems. [View Full Paper]

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THE LAYOUT OPTIMIZATION APPROACH FOR MINIMIZING THE RESIDUAL MAGNETIC OF MICRO- AND NANO-SATELLITES

Shucai Liu,[*] Tao Sheng,[†] Xianqi Chen[‡] and Zhicheng Song[§]

With the rapid development of commercial spacecraft, micro- and nano-satellite missions have been proposed for more sophisticated objectives such as remote-sensing and astronomical missions. Taking Japan's Nano-JASMINE satellite as an example, in order to achieve the goal of estimating the exact position of stars and updating the star catalogues, it is required that the attitude determination accuracy of the satellite can reach 0.05 deg and the attitude control precision can reach $4 * 10^{-7}$ rad/s. For the traditional satellite, the residual magnetic moment can be neglected. However, for the micro- and nano-satellite, the residual magnetic moment is the major disturbance torque and thus it is a non-negligible disturbance, especially for satellite conducting some observation missions that needs high-precision controllability.

To minimize the influence of residual magnetic on satellite attitude, it is found that placing the satellite components in the proper positions makes a feasible method. However, there are few researches involving this topic. In this paper, the satellite layout optimization approach to reduce the residual magnetic is presented. In addition to the objective of minimizing the residual magnetic, some layout design constraints, including non-overlap constraint, system centroid constraint and system inertia angles constraint, are taken into consideration in our research. Firstly, the magnetic dipole model for satellite component is established. By measuring the magnetic field data of the component, its magnetic moment can be obtained by inverse calculation. Then the residual magnetic can be well figured out by solving the relevant equation. Secondly, a hybrid method is proposed to optimize the satellite layout design, which combines particle swarm optimization (PSO) and sequential quadratic programming (SQP). It aims to improve the search efficiency of PSO and reduce the possibility of falling into the local optima of SQP. Finally, the feasibility of the proposed method is validated by a three dimensional satellite layout case. Besides, the results show that the residual magnetic can be reduced obviously by optimizing the satellite layout scheme, which provides an alternative way to improve the performance of the satellite attitude determination control system (ADCS) and makes the micro- and nano-satellite more practical. [View Full Paper]

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HYPER-SONIC VEHICLE SAFETY FLIGHT ENVELOPE BASED ON REACHABLE SET THEORY

Ze-hong Dong,[*] Ying-hui Li,[†] Wu-ji Zheng,[‡] Chi Zhou[§] and Peng-wei Wu[**]

Aiming at the problem of longitudinal instability of hyper-sonic vehicle caused by high non-linearity and strong coupling, a nonlinear method determined the flight safety envelope, which can provide a manipulate guideline to guarantee flight safety, is proposed based on the theory of optimal control and invariant set theory. Taking a hyper-sonic vehicle as the research object, a longitudinal dynamic model is established, and then forward reachable set and reverse reachable set is calculated respectively via using the level set algorithm. Moreover, take the intersection of them as safety flight envelope. Taking advantage of the safety envelope obtained, the safety of the vehicle is judged. The results can provide guidance for the flight safety and control of hyper-sonic vehicle.

[View Full Paper]

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ALGORITHMIC METHOD OF INTEGRAL TIME FOR REMOTE SENSING SATELLITE DYNAMIC IMAGING

Huang Mei-li,[*] Cao Hai-yi,[†] Zhao Qiao[‡] and Xu Wen-xia[§]

Some satellites, such as agile satellite must image in tri-axial attitude maneuver for new imaging mode, such as one-orbit multi-stripes splicing imaging, nonparallel-ground-track imaging. This paper introduces one algorithmic method of integral time for space-born TDICCD visible camera when remote sensing satellites implement complex attitude dynamic imaging mission. This algorithmic method, computing velocity vector combined with method of coordinate trans-formation, can be used in arbitrary attitude imaging mode for remote sensing satellites. Simulation results show that the integral time computation accuracy of taking attitude angular velocity as variable can be improved up to 10~15% than that of taking attitude angular velocity as constant for typical agile satellite with 0.1°~0.3°/s angular velocity. [View Full Paper]

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ORBITAL DYNAMICS AND ORBITAL DETERMINATION

Session Chairs:
Lei Chen
Dong Qiao
Franco Bernelli Zazzera
Hanqing Zhang

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ANALYTIC SOLUTION OF NEARLY GEOSTATIONARY SATELLITE'S ORBIT EVOLUTION CONSIDERING EARTH'S NON-SPHERICAL PERTURBATION

Haitao Zhang,[*] Zhanyue Zhang[†] and Shuai Wu[‡]

A large number of spacecraft and space debris are intensively distributed in the geostationary orbit space, ranged about 200km distance in height and 15 degrees in orbit inclination. When analyzing the long-term space environment nearly geostationary orbit, in order to reduce the amount of computation, an analytic solution of orbit evolution model is necessary. According to the earth's non-spherical perturbation potential function, the main items of non-spherical perturbation for the satellites near geostationary orbit are *J20, J22, J30, J31* and *J33*. The ratio of their effect is 1.1×10^4:6.4×10^1: 3.3: 7.1: 5.5. Based on Lagrange's planetary equation, the analytic functions of the derivative of semimajor axis(a), eccentricity(e), inclination(i), argument of perigee(ω), right ascension of ascending node (RAAN, Ω) and mean longitude(λ) to time, are got under some approximations according to the orbit characteristics of the satellites near the geostationary orbit. The analytic functions of the derivative of semimajor axis to time contain only periodic items. The analytic functions of the derivative of argument of perigee, RAAN and mean longitude to time include long terms and periodic terms. Take the space objects near the geostationary orbit as an example and substitute their orbit data into the analytic functions deduced by theory and the STK's HPOP model. Calculate the daily variety of a, and the difference between the two methods is no more than 0.09 %. The derivative of e and i to time approximately equal to 0, and the two are the same. The deviation between the two methods of the variation of Ω and ω in one year is less than 0.31% and 0.43% and the deviation of the variation of λ in a week is less than 1.1%. [View Full Paper]

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AN ANALYTICAL APPROXIMATION FOR TIME-OPTIMAL GROUND-TRACK ADJUSTMENT

Haiyang Zhang[*] and Gang Zhang[†]

Orbiting satellites can achieve rapid imaging missions in operationally responsive space (ORS) by ground track adjustment. However, the current researches on this topic mainly focus on fuel optimization. In order to meet the time requirement of ORS, this paper studies the time-optimal ground track adjustment problem under the maximum available impulse. An analytical approximation of the minimum-time impulse considering J_2 effects is provided. Firstly, the flight time of the satellite under the two-body model is derived from Greenwich mean sidereal time. Based on this expression, an analytical approximation for the optimal maneuvering position is obtained. Then, by equaling two J_2-perturbed flight-time equations from Greenwich mean sidereal time and Kepler's equation, and using Gauss's variational equations (GVEs), a fourth-order polynomial of the transverse impulse component is derived. Finally, an analytical impulse vector excluding the radial component is obtained. Using this approximate analytical solution as an initial guess, the accurate numerical solution for the impulse vector is obtained by Newton iterations. When the maximum impulse is 2 km/s, the numerical results for different initial inclinations show that the response time to the target of the minimum-time solution is shorter by 1~2 hours than that of the minimum-fuel solution. [View Full Paper]

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ANALYSIS OF FUEL-OPTIMAL ORBITAL TRANSFER TO GEOSYNCHRONOUS ORBIT USING ELECTRIC PROPULSION

Rui Zhang,* Ran Zhang† and Chao Han‡

Electric propulsion has been applied to orbital transfer on account of its high specific impulse. To minimize the fuel consumption, the problem of fuel-optimal orbital transfer to geosynchronous orbit is calculated and analyzed in this paper. The indirect approach is applied to the optimization of the orbital transfer to geosynchronous orbit. The calculus of variations and the Pontryagin's maximum principal are applied to the transformation from an optimal control problem to a two-point-boundary-value-problem of differential equations. The two-point-boundary-value-problem is solved by the unscented Kalman filter parameter estimation algorithm, which is of larger convergence domain and gradient-matrix free. In this paper, the influence of the initial orbit states and the J2 perturbation on the fuel consumption is analyzed through multiple numerical simulations. The results show that the optimization method is effective and the influence on the fuel consumption provide some valuable engineering guidance. [View Full Paper]

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GEOMETRY PROPERTIES ANALYSIS ABOUT RESONANT ORBITS IN EARTH-MOON SYSTEM

Li-Bo Liu,† Ying-Jing Qian,† * Xiao-Dong Yang† and Wei Zhang†

The initial geometry properties about resonant orbits in the Earth-Moon system are investigated. It is found that some initial geometry properties, such as eccentricity and initial phase, provided by two-body theory cannot result in resonant orbits in circular restricted three-body problem (i.e. CRTBP) due to the gravitational capture of the Moon. When closest point of a resonant orbit is in the Moon's sphere of influence (66200km) or the Kepler energy to the Moon is non-positive, possible flyby or weakly capture can happen. The position of the closest points to Moon and the Kepler energy distribution with variations of the eccentricity and initial phase are obtained, and the range of eccentricity and initial phase that cannot result in resonant orbits in CRTBP are also given. Examples of the resonant orbits in 1:2, 1:3 and 1:4 exterior resonances and 2:1 interior resonance are provided to verify the analysis, it's found that the method which judging the closest distance between spacecraft and Moon is more accurate. [View Full Paper]

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RETROGRADE GEO ORBIT DESIGN METHOD BASED ON LUNAR GRAVITY ASSIST FOR SPACECRAFT

Renyong Zhang*

In this paper a design method for changing the inclination of an orbital spacecraft from the ascending orbit to the retrograde orbit is presented. Firstly, revealing the mechanism of the lunar gravity assist, and maximum change capability of the spacecraft orbit parameters will be obtained, based on the Lagrange planetary equation; Secondly, studying the flight mechanism to transfer the geocentric orbital spacecraft to the geocentric retrograde orbit; Finally, the orbit technology from the forward GEO to the retrograde GEO is designed, and the technical application method in the actual orbit design project is proposed. [View Full Paper]

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ORBIT DETERMINATION FOR MICRO SATELLITE IN CISLUNAR SPACE BASED ON MACHINE VISION

XU Yun and WANG Zhaokui*

A novel orbit determination methodology for micro satellite in cislunar space based on machine vision is proposed. Only two optical cameras and a set of attitude sensor are in need to equip the satellite. The concept of orbit determination is to calculate the intersection of two lines-of-sight: one directs from the satellite to the earth and the other directs to the moon. The determination of line-of-sight is realized based on machine vision. This paper introduces UKF algorithm to re-duce positioning error and solve singular problem when satellite approaching the earth-moon line. A simulation is carried out to demonstrate the positioning accuracy when using this orbit determination method.

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EARTH–MOON LOW-ENERGY TRANSFER TRAJECTORY BY PATCHING WITH THE INVARIANT MANIFOLD TUBES

Yue Zheng,* Binfeng Pan† and Shuo Tang‡

In this paper, an Earth-Moon low-energy transfer trajectory design method in the planar circular restricted three-body problem is proposed. This proposed method patches two trajectories by a modified Poincaré section, with equal and non-equal Jacobi constant. One trajectory emanates from the stable invariant manifold tube of the Lyapunov orbit associated with the libration point, and another trajectory is from the period orbit around the Earth. The velocity is changed at the patching point by two ways, by adjusting the velocity direction with an equal Jacobi constant or the velocity magnitude along with the varying Jacobi constant. Several candidate low-energy transfer trajectories could be obtained by this proposed method, among which a suitable trajectory could be selected via the trade-off between fuel and flight time. Finally, extensive numerical simulations are implemented to demonstrate the effectiveness of the proposed method. [View Full Paper]

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GLOBAL SEARCH FOR PERIODIC ORBITS IN THE VICINITY OF A BINARY ASTEROID SYSTEM

Yu Shi,[*] Yue Wang[†] and Shijie Xu[‡]

Periodic orbits are important keys to understand the motion of a massless particle in the vicinity of a binary asteroid system. Due to the complex gravitation generated by the irregular-shaped asteroids, it is difficult to generate periodic orbits with an analytical method, except in the linearized dynamical environment within a small region about the libration points. This paper has presented a numerical method to search the three-dimensional periodic orbits in a global space. The grid searching method is used to find nearly periodic orbits and then the shooting method is used to get the accurate periodic orbits. The method is applied to the binary asteroid (66391) 1999 KW4 to solve the periodic orbits near the binary system. The periodic orbits are then classified into five categories based on their shapes and locations. The search method can also be used to find periodic orbits in the vicinity of other binary systems. [View Full Paper]

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SEARCHING FOR TRAJECTORIES TO ASTEROIDS USING SOLAR SAILS

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This paper describes trajectories to asteroids using solar sails as a propulsion system. Asteroids are an interesting target for space exploration for scientific and technological missions, but also present potential collisions to the Earth to be avoided. In this work the dynamics of the solar sail is described and the equations are presented. Several trajectories for a spacecraft to reach an asteroid are shown, with the goal of mapping trajectories for a mission designer to choose from. The main elements involved in the trajectory are measured, like the velocities, angle of collision, etc. Using those data any type of mission can de designed. [View Full Paper]

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AN ELECTRIC-PROPULSION-BASED MERCURY ORBIT TRANSFER STRATEGY SUBJECT TO THIRD-BODY PERTURBATION

Shunan Wu,* Shenghui Wen,† Xue Ma‡ and Zhigang Wu§

This paper investigates the electric-propulsion-based Mercury orbit transfer problem subject to the third-body perturbation. To construct feasible onboard transfer strategy via low-thrust acceleration, a novel direct approach, to compute suboptimal trajectory, is proposed. The original problem is subsequently converted to parameter optimization problem in which only a small number of parameters related to the control laws need to be optimized. The numerical results show that the proposed method, unlike traditional algorithm, is less sensitive to the initial value, and could rapidly and accurately converge to a suboptimal value. [View Full Paper]

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NUMERICAL STUDY ON THE MOTION OF SURFACE PARTICLES FOR THE ASTEROID 101955 BENNU

Yonglong Zhang,* Xiangyuan Zeng† and Christian Circi‡

Asteroid 101955 Bennu is the target asteroid of the ongoing asteroid sample return mission OSIRIS-Rex from NASA. In the mission, the spacecraft is scheduled to rendezvous with Bennu in August 2018. Investigating the dynamics of surface motion can offer guidance for further hopping landers or even sample return missions on Bennu or similarly irregular-shaped asteroids. This paper presents the free motion of some particles on and above the surface of the asteroid Bennu. The concepts and equations that govern the motion of a particle on and above the surface of an asteroid are briefly introduced. Trajectories of a number of particles' free motion are numerically calculated. Initial positions of those particles are all given on the surface of Bennu and their initial velocities are arbitrarily selected as in this preliminary study. The distribution of final locations of those sample particles is summarized and analyzed. Both the gravitational potential and its effective potential on the surface of Bennu are calculated to give a possible reason for the aforementioned distributing characteristics. [View Full Paper]

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REVIEW ON SATELLITE ORBITAL DETERMINATION TECHNOLOGY OF ASTEROID EXPLORATION

YANG Huixin* and ZHANG Zhiwei†

Asteroid exploration is of great scientific and practical significance, which puts forward higher requirements for the determination of satellite orbits for asteroid exploration missions and for the relative orbit determination of satellites formation. High precision orbit determination is the base and key technology of asteroid exploration. In this paper, the asteroid exploration activities that have been carried out in various countries are summarized, and it also summarized the methods of satellite orbit determination, including GPS method, star angular distance measurement, indirect method of star refraction, and the method of satellite orbit determination by measuring geomagnetic field, and X-ray pulsars method, and so on. The research status, application scope, emphasis and difficulty of each method are also studied. Finally, the development trend of orbit determination technology of asteroid probe satellite is also analyzed. [View Full Paper]

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AN ANALYSIS OF THE PORK-CHOP PLOT FOR DIRECT AND MULTI-REVOLUTION FLYBY MISSIONS

Davide Menzio[*] and Camilla Colombo[†]

The porkchop plot is an extremely useful tool that was developed to efficiently identify families of trajectories with low characteristic energy difference, over different launch/arrival dates and time of flights for a specific interplanetary journey. This preliminary trajectory modeling has been applied to several and successful missions, Voyager included, however, in authors opinion, it has never been fully exploited nor deeply investigated. Indeed, general applications focus the attention only to minimum solutions while high delta-vs are not questioned.

In this paper, a thorough analysis for direct and multi-revolutions trajectories is performed and investigates the location and the shape of the minimum. Purely geometric relations enable a quick identification of the minimum solution. It is possible therefore to constrain the resolutions of the Lambert's problem to a confidence region around the minimum, avoiding to run unnecessary simulations.

An analysis of gravity assists for direct transfer, extensible to the multi-revolution one, is performed by stacking porkchops one on an another in the 3D space. This can be done in a purely graphical way, considering the specific energy at departure and arrival and the surfaces associated to how well the infinity velocities patch at the flyby.

In the end, a tool to further constrain the search space for the post-encounter leg is obtained by studying the maximum/minimum variations of the semi-major axis and eccentricity induced by close/distant encounter with the respect to their desired value.

The purpose of this paper is to show that, when direct solutions produce unfeasible results, multi-revolutions are always possible. Secondarily, a quick way to represent gravity assist trajectories on the 3D porkchop plot is presented and compared with the solution offered by the search space identification tool. [View Full Paper]

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DESIGN AND STABILITY ANALYSIS OF FROZEN ORBITS AROUND BENNU

Feida Jia,[*] Dong Qiao,[†] Xiangyu Li[‡] and Hongwei Han[§]

Bennu, a carbon asteroid, has been widely studied in recent years. Its characteristics, such as geological and dynamic characteristics, have been studied in previous studies. Being potentially hazardous to Earth, exploration missions to Bennu are great interests and necessary. Frozen orbit is commonly used in asteroid exploration because of its stability, long orbit duration time and other specialized advantages for observation. This paper mainly focuses on the design of frozen orbits in the vicinity of Bennu. In this paper, the dynamic model takes asteroid's gravity expressed by higher-order zonal harmonic coefficients and solar radiation pressure into account. A double-averaging technique is used to design the frozen orbits near Bennu. The design method proposed in this paper is practical and can be applied in exploration missions to Bennu in the near future.

[View Full Paper]

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NUMERICAL CONSTRUCTION OF HALO ORBITS BASED ON INVARIANT MANIFOLD TECHNIQUE WITH TWO DOMINANT MOTIONS

Jian-Yu Guo,[†] Ying-Jing Qian,[†] [*] Li-Bo Liu[†] and Wei Zhang[†]

Libration points are the five equilibrium solutions in the circular restricted three-body problem (i.e. CRTBP), including three collinear points and two triangular libration points. Studies about probes moving around orbits in the vicinity of the libration points have theoretical significance. In this study, we extend the method proposed by Qian and Yang (Astrophys Space Sci 362(8):136,2017), (Nonlinear Dyn 91(1):39-54,2018). Two dominant motions are considered for the construction of spatial halo orbits. Based on the invariant manifold theory, the ξ and ζ-component motions are selected as the dominant motions for halo orbits, η-component motion as slave motion. The invariant nonlinear asymptotic relations between the two dominant motions and the slave motion are obtained. By employing the relations among the three directions, the three-dimensional system can be transferred into a two-dimensional problem. As one of the applications, the invariant nonlinear relations in polynomial expansion form are used as constraints to obtain numerical solutions by differential correction. The nonlinear asymptotic-relations among the directions provide an alternative point of view to explore the overall dynamics of periodic orbits around libration points with general rules. Numerical simulations verify the efficiency of the proposed method. [View Full Paper]

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HIGH-ORDER STATE TRANSITION POLYNOMIAL WITH TIME EXPANSION BASED ON DIFFERENTIAL ALGEBRA

Zhen-Jiang Sun,* Pierluigi di Lizia,† Franco Bernelli Zazzera‡ and Ya-Zhong Luo§

In this study, the problem of propagating an initial orbital state around its reference value to a variable final time is addressed. Based on the differential algebra (DA) technique, a high-order state transition polynomial with time expansion (STP-T) method is developed. The STP-T is a high-order Taylor approximation of the final orbital state expanded around the reference initial state and the propagation time. Thus, given the initial displaced orbital state, any state around the reference final time can be efficiently obtained by evaluating the corresponding polynomial. Furthermore, an asynchronous-order scheme for STP-T is presented, which enables the STP-T to have different orders with respect to the variables with different nonlinearity. Besides, the manual derivation and integration of the high-order variational equations is avoided in the DA framework, which makes the order of the polynomial flexible and the method versatile for various dynamics. The simulation results indicate that the STP-T supplies a good approximation of the final state in pure and J2 perturbed Keplerian dynamics, and in a nonlinear relative motion. [View Full Paper]

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AUGMENTED UNBIASED MINIMUM-VARIANCE INPUT AND STATE ESTIMATION FOR TRACKING A MANEUVERING SATELLITE

Yuzi Jiang* **and Hexi Baoyin†**

This study investigates the problem of tracking a non-cooperative satellite performing continues maneuvers. An augmented unbiased minimum-variance input and state estimation (AUMISE) method is developed for estimating the state and the maneuver acceleration in real time. The maneuver acceleration estimation of the proposed method is proven to be more accurate than the original unbiased minimum-variance input and state estimation (UMVISE) method. Approaches based on the measurement residual and the acceleration estimation are developed for maneuver start and end detection. The estimation method is switched between the AUMVISE method and the classical extended Kalman filter (EKF) to obtain an accurate tacking result during the maneuver period and the non-maneuver period of the target. Simulation results show that the proposed method has a suitable maneuver detection delay and outperforms the UMVISE method in estimating the state and maneuver acceleration. [View Full Paper]

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STATION-KEEPING OF LIBRATION POINT ORBITS BY MEANS OF PROJECTING TO THE MANIFOLDS

Hanqing Zhang,[*] Fang Zhou[†] and Shuang Li[‡]

This paper is devoted to the study of applying numerical and Semi-analytical techniques to robustly control the collinear libration point orbits (LPOs). Two complementary methods are proposed exploiting the hyperbolic dynamics of the collinear libration points. The first is a semi-analytical projection method which is based on the reduction to the center manifold process. After the transformation from synodic coordinates to center manifold coordinates is derived, the error state can be projected to center manifold or its stable manifold by introducing a Station-keeping Delta-V, eliminating the unstable component. The second method is fully numerical. After the formulation of the libration point region, an escape time algorithm is designed to effectively project the error state to the center manifold. By applying these algorithms to the collinear libration points of Earth–Moon system, it has been demonstrated that the proposed methods can handle the station-keeping problems of various types of LPOs in a unified manner and is robust over a wide range of energy levels. [View Full Paper]

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INFLUENCE OF UNSTABLE DYNAMICS ON ORBIT DETERMINATION WITH X-RAY PULSAR NAVIGATION

Yang Zhou,[*] [†] Mai Bando,[‡] Shinji Hokamoto[§] and Panlong Wu[**]

This paper explores the influence of unstable dynamics on orbit determination. A halo orbit about the Earth-Moon L2 is considered to be the nominal orbit and the dynamics model is constructed based on the Earth-Moon circular restricted three body problem. X-ray pulsar navigation method is introduced for orbit determination that is performed by Kalman filter. Simulation results show that unstable manifold of halo orbit dominates the growth of orbit-determination error and the corresponding uncertainty. However, when the orbit-determination measurements are incorporated in, the results change and are greatly influenced by the characteristic of the X-ray pulse measurements.

[View Full Paper]

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REACHABLE DOMAIN FOR SATELLITE WITH CONTINUOUS LOW-THRUST BASED ON THE TWO BODY MODEL

Haoran Gong* and Shengping Gong†

The reachable domain (RD) for satellite with continuous low-thrust that initially orbits Earth in a circular orbit is investigated. The standard Two Body model is employed. Establishing a frame of reference moving along with the RD, we determine the boundary of the RD by looking for the largest displacement the satellite may accomplish in an arbitrarily chosen spatial direction. Thus the RD solving problem is converted into a series of finite-time optimal control problems which can be solved by a Newton's shooting method. By traversing all the spatial attitude angles we finally obtain the numerical solution of the RD. [View Full Paper]

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TIME-EXPLICIT ANALYTICAL SOLUTION TO NEAR-COPLANAR, NEAR-CIRCULAR ORBITAL RELATIVE MOTION

Qingtang Mao,[*] [†] Shuquan Wang[‡] and Yang Gao[§]

Time-explicit analytical descriptions of near-coplanar relative motion with a circular reference orbit is investigated. As far as we know, using the linearization approximation in the form of Cartesian coordination, a simple form and time explicit analytic solution, which is the solution of the Clohessy-Wiltshire equation, is given. To enlarge the effective description range, the solution of the Clohessy-Wiltshire equation in the form of curvilinear coordinates is also proposed. However, it is not time-explicit and its form is complex. In this paper, Lagrange's generalized expansion based on the orbital element is introduced to approximate the dynamics equation of relative motion into an integrable form, and then the undetermined coefficient method is applied to obtain the analytical description of the relative motion. In addition, a new set of six initial parameters is used to describe the relative states. The corresponding analytical solution is convenient for describing the geometric features of the long-range relative motion. Based on this analytical solution, it is found that the relative motion configuration is always a 2-by-1 ellipse except that the type of the formation is leader-follower in circular orbits. The numerical simulations show that the analytic solution has a high accuracy when describing a long distance relative motion. [View Full Paper]

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RELATIVE ORBITAL MOTION OF TWO CHARGED OBJECTS NEAR A SPACEBORNE RADIALLY-DIRECTED ROTATING MAGNETIC DIPOLE

Chao Peng,* Changxuan Wen† and Shuquan Wang‡

The relative orbital motion of two charged objects near a spaceborne magnetic dipole are presents in this study. Assuming that a spacecraft generating a rotating magnetic dipole moves in a Keplerian circular reference orbit and two constantly charged objects move close to the artificial magnetic field, which indicates that both the Lorentz force and coulomb Force acting on the charged objects are taken into consideration, a nonlinear dynamical model of the proposed relative orbital motion is established based on the Hill-Clohessy-Wiltshire (HCW) equation and the system parameters such as the charge-to-mass ratio of the charged object, the moment and rotating rate of magnetic dipole (the axis of the dipole is assumes to be perpendicular to the reference orbital plane), and the angular velocity of the circular reference orbit. Firstly, the equilibrium points of the system, integral constant, and zero-velocity curves for the proposed relative motion are derived and bounded periodic orbits are searched out by using Poincare maps in terms of the zero-velocity curves. Moreover, the stability characteristic of equilibrium points were analyzed and planar periodic orbits near the equilibrium points were numerically computed by differential correction. The presented periodic orbits of relative motion in this article are different from those in traditional satellite formation flying, which suggests potential applications of the presented periodic orbits, such as propellantless satellite formation maintenance and noncontact capture of electrostatically charged space debris.

[View Full Paper]

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THE OPTIMAL PROCESS NOISE VARIANCE MATRIX IN THE EQUIVALENT NOISE METHOD

Nan Wu,[*] Feng Wang, and Fankun Meng

Equivalent-noise approach is extensively applied for it's simple and stable. However, the key to its application is that the time-varying equivalent process noise variance corresponding to the unknown input should be given. This paper analyzes the biasness of equivalent noise approach estimation, deduces the analytical expression of the optimal process noise covariance matrix in the equivalent noise approach, gives the quantitative relationship between the optimal process noise covariance matrix and the systematic random noise, state estimation bias and unknown input, finally the application of this method is proved by the example of trajectory estimation problems of Maneuvering reentry vehicle (MaRV). This method is not directly used for target tracking, but plays some roles in the tracking algorithm design: to provide theoretical basis for time-varying process noise variance construction or adaptive filtering algorithm design, and the optimal estimation results can be used to evaluate the performance of adaptive filtering algorithm related. [View Full Paper]

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OPTIMAL AEROASSISTED ORBITAL RENDEZVOUS AND INTERCEPTION

Hongwei Han,[*] Dong Qiao[†] and Hongbo Chen[‡]

Optimal trajectories of aeroassisted orbital rendezvous and interception can be found when considering the general elliptic initial and target orbits. In this paper, both the minimum-fuel and minimum-time cases are taken into account so as to analyze the corresponding optimal results. Specifically, the initial state constraints at deorbit position and atmospheric entry have been re-derived firstly under the premise that the waiting time before the deorbit maneuver is taken as an optimization variable. Secondly, considering the limitation of factors such as heating-rate and load, the optimal trajectories of the aeroassisted orbital rendezvous with minimum-fuel and minimum-time are given. Besides, the profiles of relevant control variables are shown. Because the interception does not need terminal brake impulse strictly, the minimum-fuel aeroassisted interception problem under total time constraint is solved. The result indicates that the time constraints should be imposed prudently because they will increase three different kind of loads effected on chase vehicle. Finally, when under different maximum allowable distance of interception position situation, the optimal results of the minimum-time interception are conducted in detail. [View Full Paper]

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A DIMENSION-REDUCTION SOLUTION OF FREE-TIME DIFFERENTIAL GAMES FOR SPACECRAFT PURSUIT-EVASION

Zhenyu Li,* Hai Zhu,† Zhen Yang‡ and Yazhong Luo§

This paper proposes a dimension-reduction method for free-time pursuit-evasion games between two spacecraft near circular orbit. For the 6-dimension dynamics governing the motion of a spacecraft, the free-time differential game can be modeled as a 24-dimension two-point boundary value problem (TPBVP). Based on the circular-orbit variational equations and relationships between the co-states of two spacecraft, this paper transformed the 24-dimension TPBVP into a set of 4-dimension nonlinear equations so that it can be efficiently solved. Then a method of combining the differential evolution algorithm and the Newton method was utilized to solve nonlinear equations numerically. Finally, the optimal control laws satisfying terminal constraints strictly were obtained.

[View Full Paper]

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LONG-TERM FROZEN ORBIT DESIGN AND STABILITY ANALYSIS

Hang Qie,[*] Jing Cao[†] and Hengnian Li[‡]

Frozen orbit is applied widely in regional observation missions for the stable position of the apse line. However, in real environment the apse line of the frozen orbit always deviates from its design position, which results in frequent orbit maintain control. Searching for long-term stable frozen orbit can reduce the control frequency and save fuel. Aiming at the solution to long-term stable frozen orbit, the frozen equations are analyzed and a numerical differential modified method searching for frozen conditions is proposed in this paper. Firstly, the instability of the frozen orbit under the second-order zonal harmonics is proved by the Lyapunov stability theory, along with the simulation of the Molniya orbit as an example. Secondly, the analytical frozen conditions considering higher order zonal harmonics, i.e. J_7, is derived, and the orbit under which is also proved to be unstable. In order to achieve long-term stable frozen orbit, a numerical differential modified method searching for the frozen conditions is proposed and discussed. The initial value of the searching method is provided by the frozen condition under the second-order zonal harmonics. And higher order zonal harmonics and other perturbations can be considered in this method. Finally, simulations verified that on the orbit of 8000km semimajor axis and 56° inclination under J_{13} zonal harmonics, and the mean eccentricity does not exceed $\pm 5\times10^{-6}$, and the mean argument of perigee does not exceed ±0.3° during 3000 days. [View Full Paper]

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ORBIT DECAY PREDICTION OF UNCONTROLLED SPACECRAFT BASED ON FILTER PARAMETER IDENTIFICATION

GAO Xinglong,* CHEN Qin,† LI Zhihui‡ and DING Di§

The orbit decay determination of large-scale spacecraft is a worldwide problem. Unscented Kalman Filter (UKF) method is firstly used to generate the initial mean orbital elements for the orbital evaluation as the TLE sets. The SGP4 model is corrected by the aerodynamic coefficients of self-rotating spacecraft calculated by the local analytical method in rarefied transitional regime, and the perturbation of aerodynamic forces in corresponding altitude is analyzed. Finally, the secular prediction of uncontrolled spacecraft in LEO orbit evaluation is proposed, the results show that accuracy of the novel model is good, which provide supports for the prediction of later reentry point. [View Full Paper]

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NEW SOLUTION FOR THE CLASSICAL LAMBERT'S PROBLEM BY USING T-H EQUATION

Qing Chen,[*] Lei Chen[†] and Kebo Li[‡]

Lambert's problem is two-body boundary-value problem which is usually used to solve orbit problem. Generally, the solution of Lambert's problem is based on two-body model, and under the influence of orbit perturbation, the target position could have a big deviation. Thus, it is necessary to explore a new method to solve Lambert's problem more directly and more efficiently based on a more accurate earth gravitational field model. In this paper, the analytic state transfer matrix based on T-H equation in the elliptical orbit is used to get the velocity increment directly. In the simulation, the method based on T-H equation is compared with Herrick method and pervasive method. And its feasibility is validated. [View Full Paper]

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DECOMPOSITION ANALYSIS OF SPACECRAFT RELATIVE MOTION UNDER PERTURBATIONS

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The relative motion model is the major foundation of the distributed space system researches. Recently, the development of the giant constellation system makes the long-term maintenance of the distributed space system more difficult. It is necessary to study the analytical model of large scale relative motions for the long-term maintenance problem under perturbations. Then, focusing on the higher-fidelity relative motion model expressed by classical orbital elements, the decomposed model of spacecraft relative motion was proposed by separating the orbital elements in two different parts, which reflect the circling motion around chief, and their overall motion relative to chief respectively. Characters of each part were analyzed to get their evolutions caused by perturbed orbital elements and to find key factors that causes long-term drifts. Accuracy and stability of the decomposed model were simulated both in Kepler orbit and perturbed orbit at last. Results show that the decomposed model proposed in this paper could be used for the design and maintenance of the distributed space systems without distance scale limitation. [View Full Paper]

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ANALYSIS OF ORBIT CONTROL ERROR PROPAGATION VIA CADET

Ying Zhang,* Wei Li,† Xijing Wang,‡ Bo Yuan§ and Jing Ma**

When spacecraft maneuvers because of all kinds of error factors. The covariance propagation equations need to be developed for the main error factors when spacecraft maneuvers. Desired effect has been obtained for orbital error propagation by covariance technique. But the dynamic model is over simplified. Therefore, the inherent characteristics of the nonlinear system are neglected. In this paper, the orbital error propagation equations are proposed by real linearized method and quasi linearized method, and the perturbation effect of the equations is taken into consideration. Through numerical simulations. The error of orbit prediction is obtained by reference to Monte Carlo method. The results of the proposed orbital error propagation equations are compared with that of real linearized method and quasi linearized method. Results show: the quasi linear model has higher accuracy than the linear model. Orbital control error propagation equations are also proposed by quasi linearized method. The simulation analysis show: the size deviation of the control force has the greatest influence on the error propagation accuracy of orbital control. [View Full Paper]

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A METHOD FOR GEO SATELLITE STATION KEEPING EQUIPPED WITH ELECTRIC THRUSTERS

Kejie Gong,* Ying Liao† and Mingzhu Bian‡

The electric propulsion applied to GEO satellite station keeping was studied. In order to conveniently apply the electric propulsion system to the station keeping the decoupled control strategy of east-west and north-south was adopted. A station keeping strategy based on a two-week forecast is given. According to the GEO satellite orbital drift, the optimal impulse maneuver and maneuvering time are calculated, and then maneuvering intervals of low-thrust is calculated. The north-south station keeping is daily performed and the east-west station keeping is only performed when the satellite moves out of the dead band. The simulation of one-year station keeping of the GEO satellite at east longitude 115° is performed. Then the influence of thrust magnitude of the thruster on the station keeping and fuel consumption was studied. The results show that the longitude is almost kept within the dead band of ±0.05° and the latitude is kept within that of ±0.01°. This strategy can be effectively applied to GEO satellite station keeping.

[View Full Paper]

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CORRELATION CHARACTERIZATION OF ORBITAL PREDICTION ERROR BASED ON RELATIVE MOTION THEORY AND ITS APPLICATION

Xian-Zong Bai* **and Lei Chen†**

Considering that the orbital prediction error is much smaller than the radius of space object, the true state and predicted state of space object can be seen as two objects: a real one and a virtual one, and the prediction error can be seen as the relative motion between them. The negative correlation characteristics of position and velocity error in the case of near-circular orbit are studied based on the geometrical model of relative motion. The along-track position error and the radial velocity error are negative correlated, so are the radial position error and the along-track velocity error. The C-W equations and the historical TLE data are used to validate the correlation characteristics. The application of negative correlation characteristics in the determination of initial error covariance is discussed; the results indicate that the consideration of negative correlation can effectively mitigate the increase of initial error. [View Full Paper]

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SPACE STRUCTURES AND TETHERS

Session Chairs:
Eberhard Gill
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A MULTI-STAGE DRAG DE-ORBIT STRATEGY AND OPTIMAL COMMANDS DESIGN FOR A TETHERED SYSTEM DURING LARGE SPACE DEBRIS REMOVAL

Tao Wei,[*] Jingnan Di,[†] Zhongyi Chu[‡] and Jing Cui[§]

There is a serious challenge to the safe operation of orbiting satellites as the number of space debris on the geosynchronous orbit increases. Consequently, the active removal of space debris has drawn wide attention in recent years. And a tethered system is considered to be a promising method to remove debris in high orbit with its low power consumption and costs. However, the flexible tether of the system can bring the coupling of the orbit motion, the sway motion and the variation of large debris attitude, which means great danger in deorbiting phase and bring a huge challenge in later control. Hence, in this paper, aiming to de-orbit large space debris safely with a tethered system, a multi-stage horizontal drag de-orbit strategy is designed to deal with the coupling caused by a flexible tether. Based on that, optimal commands are planed using Gaussian pseudo-spectral method to achieve decoupling of the orbit motion, the sway motion and the variation of target attitude. Finally, numerical simulation is established to follow the planned commands by tension and tug thrusts in large space debris removal to verify the effectiveness of the proposed de-orbit strategy. [View Full Paper]

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DYNAMICS OF THE TETHERED SPACE-TUG SYSTEM FOR THE REMOVAL OF GEO DEFUNCT SATELLITE

Keying Yang,[*] Shan Lu,[†] Rui Qi,[‡] Yu Liu[§] and Jingrui Zhang[**]

The tethered space-tug system is recognized as one of the most promising techniques to reduce the population of space debris. In this paper, the debris is specified as a large defunct GEO satellite equipped with one or two flexible appendages. A precise 3D dynamic model using Kane's method is derived. The dynamical behavior of the system is studied via numerical simulations, and some characteristics are revealed through this process.

[View Full Paper]

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EXPERIMENT-BASED CONTACT DYNAMIC MODELING FOR DETUMBLING A DISABLED SATELLITE

DUAN Wenjie,[*] [†] ZHANG Haibo,[*] [†] WANG Dayi[‡] and ZHU Zhibin[*] [†]

The contact force model is very important for detumbling research. In this paper, we focus on the contact model research for detumbling a disabled satellite at high spinning speed by robot arm with flexible end-effectors. Physical experiment is performed on two end-effectors with alloy wire and fiber sheet. The contact model is established based on the data by experiment. [View Full Paper]

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DESIGN AND SIMULATION OF A NON-COOPERATIVE TARGET CAPTURE SCHEME BASED ON THROWING ROPE

G.b Zhang,[*] G.b Zhang,[†] Z.W. Feng[‡] and Q.Q Chen[§]

In view of the shortcomings of the short capture distance and the lack of adaptability to the target shape for the current non cooperative target capture scheme. A new scheme was put forward in which the capture device connected with a rope is launched from the capture satellite at first, and then the sticky rope thrown by the arresting device to winds round the target. Based on absolute nodal coordinate formulation and absolute coordinate method of rigid body modeling, the multi-body dynamics model of the system is established and the whole capture process is simulated. The results show that the sticky rope can achieve the entanglement of the target, the tether and the sticky rope will not be broken during the capture process.

Keywords: Space operation; ANCF; Dynamics. [View Full Paper]

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DYNAMICS OF THE TETHERED GEO DEFUNCT SATELLITE WITH FLEXIBLE APPENDAGES

Anrui Shi,* Rui Qi,† Shan Lu, Yu Liu‡ and Jingrui Zhang§

There are many defunct satellites in geostationary orbit (GEO). The existence of them makes the GEO orbit crowded. And defunct satellites a potential source of great number of small space debris who poses a threat to the safety of well-working satellites. By considering the vibration many destroy the flexible appendages of defunct satellites, this paper studied the dynamic of defunct satellites removal by space net. This paper simplifies the tug-tether-net-defunct satellite system into a TST system. The flexible panels are considered as thin plates with one fixed edge and three free edges. The TST system is analyzed, and the kinetic energy, gravitational potential energy, elastic potential energy and generalized force of system are obtained. The equations of motion of the formation are obtained by using Lagrange's equation. [View Full Paper]

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EFFECTS OF SYSTEM PARAMETERS ON ATTITUDE AND ORBITAL DYNAMICS OF ELECTRODYNAMIC TETHER SYSTEM

Yuwei Yang,* Lei Lei,† Yuhang Shao,‡ Hong Cai§ and Shifeng Zhang**

The mass of the main satellite, the mass of the sub-satellite, the mass of the tether, and the current in the tether for the electrodynamic tether system are regarded as system parameters. The purpose of this paper is to investigate the effects of these parameters on the attitude dynamics and the orbital dynamics. Based on some assumptions, the attitude dynamic equation and the orbital dynamic equation of the system in the inclined elliptical orbit are built, respectively. To obtain the effect of each parameter on the attitude dynamics, the stability of the periodic solution of the attitude dynamic equation and the failure time of the attitude libration are investigated for different values of system parameters, respectively. To obtain the effect of each parameter on the orbital dynamics, the deorbit time is used to measure the effect on the orbital dynamics. In addition, the attitude libration is considered in the orbital dynamics. Simulations are used to analyses the trend and change laws of the effects of these parameters on the dynamics of the system. Synthesize the results of the effects of the system parameters on the attitude and orbital dynamics, some theoretical basis and referential suggestions are provided for the actual design and on-orbit operation of the electrodynamic tether system. [View Full Paper]

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ATTITUDE SENSORS AND ACTUATORS

Session Chairs:
Arun Misra
Kebo Li
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THREE-DOF ORIENTATION MEASUREMENT BASED ON OPTICAL SENSOR FOR REACTION SPHERE

Guanghui Liu,* Fei Sun,† Jun Zhou‡ and Jianguo Guo§

Reaction spheres, serving as the core unit to provide three-axis attitude control, are promising alternatives to conventional momentum exchange devices for the Attitude Determination and Control System (ADCS) due to its three-degree-of-freedom (three-DOF) rotation with an integrated device. The measurement of spherical rotor orientation is critical to the close-loop control for reaction sphere actuator as well as the angular momentum management via the ADCS. Nowadays, the techniques for simultaneous measurement of multiple DOF motions have already been demonstrated in various fields including industry, machinery and automation. Conventional measuring methods based on the single-axis encoder or mechanical linkages are restricted to measure complex motions, especially three-DOF motions owing to the mechanical friction and complicated structure, while the optical sensor could capture the images of rotor surface without contact and obtain the spatial rotational speed through image processing with relatively simple architecture and lower cost. In this paper, a novel speed measuring system is proposed on the basis of optical sensor for the rotor orientation of reaction sphere actuator, whose spherical rotor can be accelerated about any desired axis. Firstly, the operational principles of the optical sensor and the reaction sphere are introduced, and the mean resolution of optical sensor affected by different materials and patterns of rotor surface is studied to determine the prior surface. Afterwards, the design concept and theory of measuring system composed of three optical sensors for the three-DOF motion are presented along with the analytical model of input-output parameters. Finally, the design feasibility of sensor system for measuring the rotational rotor orientation is validated experimentally using prototype system which can achieve the rotational speed 1500 r/min and the effect of system parameters on the resolution, average error, responsivity and measuring range is analyzed by comparing the theoretical results and experimental results. The simulation results show that the optical sensor system can meet the requirements of accuracy and measuring range, and the results are expected to serve as a basis for the parameter optimization which can greatly improve the sensor performance of the reaction sphere. [View Full Paper]

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THERMAL DISTORTION ON DEPLOYABLE SOLAR PANELS OF CUBESAT IN LOW EARTH ORBIT

Syahrim Azhan Ibrahim* and Eiki Yamaguchi†

This study predicts thermal distortion that can occur on deployable solar panels of a CubeSat in low earth orbit during eclipse transition of night-day. A 3U CubeSat with four short edge deployable solar panels that point to the Sun is considered. There are three steps of modeling involved. Firstly, the time historic temperature of the solar panel is characterized. Secondly, the results obtained are used in general stress analysis using a finite element software to obtain deformation of the solar panel. Finally, the effect of solar panel motion on the attitude displacement of the satellite is examined using inertia relief method. Results show that quasi-static deformation appears due to the difference in cross-section temperature of the solar panel. Brief thermal snap disturbances are likely to take place during eclipse transitions as well. As a result, the pointing direction of the CubeSat could be disturbed in the case when the solar panels are in asymmetric configuration.

[View Full Paper]

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VISUAL-INERTIAL ATTITUDE PROPAGATION FOR SMALL SATELLITES USING UNSCENTED KALMAN FILTER

Amartuvshin Dagvasumberel[*] and Kenichi Asami[†]

Robust, accurate and efficient attitude determination system is a key component for Earth-observation small satellites. However, achieving highly accurate attitude determination and control system is challenging due to the satellite's small form factor. In this paper, we propose a visual-inertial attitude propagation approach for Earth-observation small satellites. The proposed approach integrates vision-based and inertial attitude estimation methods in an unscented Kalman filter (UKF) framework. The vision-based method employed the satellite's nadir pointing camera as the attitude sensor and the satellite's attitude information derived from captured sequential images based on Earth-observation geometrical constraints and image processing techniques. Experimental and simulation results are presented, which demonstrate the performance of the algorithm on generated visual datasets of known attitude changes and analyze the system's ability to minimize the drift of an attitude propagator. [View Full Paper]

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SPACE OBJECT SHAPE CHARACTERIZATION FROM PHOTOMETRIC DATA USING RECURRENT NEURAL NETWORK

Yurong Huo,[*] Zhi Li[†] and Yuqiang Fang[‡]

We present an approach that employs machine learning techniques to determine the most probable shape of resident space objects (RSO). Our algorithm focuses mainly on photometric data obtained from optical sensors and analysis of the computer simulation. Aiming at RSO of LEO, an identification model is trained by recurrent neural network (RNN) technique to find the shape among a number of candidate shape models. Firstly, the basic 3D shape model of the space object is established, including cylinders, pyramids, and cuboids and so on. Then, the bidirectional reflectance distribution function (BRDF) model is processed to obtain the photometric time series signals of the basic shape model and the photometric data will be used as training samples. Next, the RNN is trained with the photometric sequential data as input. Finally, new photometric timing signals obtained by optical sensors and analysis of the computer simulation are used as input to the network to identify the object shape. The initial experimental results show that the algorithm presented in this paper could determine the shape of RSO effectively and accurately, and this approach has more adaptive performance and can obtain satisfactory results. [View Full Paper]

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A SIMPLIFIED ATTITUDE FUSION ALGORITHM OF STAR-SENSOR AND GYRO

Lijun Ye,* Gang Liu,† Yanhong Yuan,‡ Jinhua Sun§ and Ying Xu**

A simplified algorithm of star-sensor and gyro high accuracy attitude fusion is put forward, by dividing the complex original dynamic system into 2 simple parts, the simplified algorithm has the characteristics of less-calculation and high-precision. Finally, comparative numerical simulations were provided to illustrate the effectiveness of the simplified algorithm. [View Full Paper]

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EXPERIMENTAL STATISTICAL ENERGY ANALYSIS OF SATELLITE STRUCTURE USING ENERGY SENSITIVITY ANALYSIS METHOD

Hongliang Zhang,* Xianren Kong† and Jiang Qin*

Statistical Energy Analysis (SEA) is an efficient method to predict wide-bandwidth noise and vibration for complex spacecraft structure. However, an analytical SEA model often exhibits errors due to unreasonable estimation of SEA parameters, such as damping loss factors (DLF) and coupling loss factors (CLF). Experimental SEA is practically used to update the model or to identify the DLFs and CLFs in a SEA prediction work. This paper proposes a hybrid SEA modeling method based on energy sensitivity analysis for experimental SEA, which can update analytical SEA model with errors using test measured data. The proposed method can minimize residuals between measured and analytically predicted energy levels by solving a nonlinear constrained optimization problem iteratively, and the SEA parameters of the analytical model are updated directly in more physical sense. A reduction technique is utilized to match the analytical subsystems with the experimental ones. In addition, the problem of ill-conditioned sensitivity matrix is investigated based on regularization method to improve the numerical stability of the algorithm.

The proposed methods are validated through several numerical simulations, which show that the analytical SEA model with error parameters can be updated successfully even with a very limited experimental data set. And then an acoustic test investigation of a satellite structure is carried out and a procedure to perform an analytically predictive SEA model updating with the measured data is summarized. It is found that the predictions of updated model of the satellite match the measured result more closely, which indicates that the hybrid SEA modeling method can enhance the ability to model the vibroacoustic behavior of complex systems. [View Full Paper]

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SYNCHRONOUS VIBRATION CONTROL OF MAGNETICALLY SUSPENDED FLYWHEEL BASED ON COMPOUND LEADING CORRECTION

ZHANG Yang,* LIU Kun† and FENG Jian‡

Aiming at the problem of the synchronous vibration caused by the rotor unbalance, Sensor Runout and Magnet Runout when the magnetically suspended flywheel rotates at high speed, this paper proposed a method based on the generalized notch filter and compound leading correction to control the synchronous vibration force. Firstly, consideration the effect of the rotor unbalance on the system alone to design a zero synchronous vibration controller. Based on the adaptive synchronous signal notch filter to inhibit the synchronous current, and in order to compensate negative displacement stiffness of magnetically bearing, based on the adaptive synchronous signal pass filter to extract the synchronous section of the displacement signal. So as to achieve zero synchronous vibration control of the magnetic bearing. Then, the effect caused by Sensor Runout and Magnet Runout on the system are added, and the analysis of the current system's residual synchronous vibration force in the time domain and the frequency domain is performed. Based on the above research, designed a synchronous vibration control strategy based on advanced feed-forward compensation to improve the controller. Finally, the rotor of the magnetically suspended flywheel rotates around the main axis of inertia. There is no synchronous vibration force of the magnetically suspended flywheel, and the simulation verified the effectiveness of the control method. [View Full Paper]

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COMPREHENSIVE ANALYSIS OF A NEW ACCELEROMETER USING AMORPHOUS WIRES GIANT STRESS-IMPEDANCE EFFECT

Jinyi Yang[*] and Meiping Wu[†]

The accelerometer which could measure the linear acceleration of the aircraft is a significant part of posture sensors. In order to improve the accuracy and decrease the size of sensors, this paper analyzes the feasibility of using Giant Stress-Impedance (GSI) effect of amorphous wires in the accelerometer. The amorphous wire is a new alloy material which has high strength and good electrical properties. The GSI effect of amorphous wires indicates that the impedance of amorphous wires could sensitively change when there is external stress, which could help calculate the acceleration. This paper introduces the study utilizing a principled model which includes a high frequency electrical part and a mechanical part to find whether the amorphous wires are suitable to be used in the accelerometer, and whether the small changes of the axial stress on the amorphous wires could been detected when the posture of the vehicle where the accelerometer installed on changes. According to the experiments, we found the fitted function, designed a triaxial GSI accelerometer model and confirmed that the GSI accelerometer have high accuracy, small size and low cost. These findings are important for the development of three-dimensional accelerometers and posture sensors in the vehicles, which also provide a new method to use amor-phous wires in sensors which need high accuracy and small size. [View Full Paper]

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IDENTIFICATION CONDITIONS AND ONLINE PARAMETER ESTIMATION FOR SATELLITE SYSTEM WITH A SWITCHING CONTROLLER

Cong Zhang[*] and Qi Zhu[†]

System identification and parameter estimation are fundamental for onboard real-time state estimation, control, fault detection, and mission planning of satellite system. In order to achieve better control performance, the controller of the satellite is commonly switched among different feedback laws, and the actuator is also switched among reaction wheel, control momentum gyro, and propellant system in different work mode, which will bring benefit for the *informative* property of the closed-loop data set according to our previous conclusion. In this paper, we study the problems related to closed-loop identification of dynamic model of a single-input single-output satellite system with switching feedbacks. Firstly, we prove that the closed-loop data set of this satellite control system without external excitation is *informative* under very mild condition. Then, a recursive weighted least-squares (RWLS) method is further developed for online parameter estimation, where the weighted factor is designed according to each work mode to balance the contributions of each mode's data. Finally, experimental results show that the estimations made by the RWLS method converge to the true values quickly. [View Full Paper]

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A TWO-LAYER FAULT DIAGNOSIS METHOD FOR GNC SYSTEM BASED ON DECISION TREE ALGORITHM

Ye Ji,[*] Yang Yang[†] and Chun Yuan Wang[‡]

As an important part of the satellite, the guidance navigation and control system (GNC) controls the satellite attitude and orbit. In order to improve the fault diagnosis of GNC systems. In this paper, the characteristics of telemeter parameters are analyzed, and a GNC system based on the decision tree algorithm that is adopted to diagnose the fault of the GNC system is proposed. The first layer diagnosis is located in the system at the component layer. The second layer diagnosis completes the fault location. The relationship between the fault and the detection point can be used to locate the fault location and assist the researchers to better predict and deal with the failure. Example of solar sensor failure point: The second fault diagnosis determines that the fault point is one of the following: 1 Full open code without signal output; 2 Monitor code output error message; 3 Code channel output error information; 4 Total open code telemetry output signal amplitude drop; Finally, the fault diagnosis system is tested by adopting this kind of two-layer diagnosis method. The results show that this method can effectively improve the intelligence, fault tolerance and versatility of GNC system fault diagnosis. [View Full Paper]

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STRUCTURAL DESIGN AND DEVELOPMENT OF A MECHATRONIC FLYWHEEL FOR MINIATURE SATELLITES

Ming Qi,[*] Dengyun Wu,[†] Shaowei Zhang,[‡] Rui Yao,[§] Pengbo Zhang,[**] Tiantian Han[††] and Jiangjuan Chang[‡‡]

A mechatronic flywheel suitable for miniature satellites is introduced in this paper. The structural design and development of the mechatronic flywheel is discussed in detail. The paper focuses on the architecture design of the flywheel, the optimum structural design processes of the sealed cover and the inertia supporting framework using Finite element analysis software. The configuration changing of the sealed cover of the flywheel is especially investigated taking emphases on its intensity and stability. Then the thickness of the sealed cover is optimized by locally strengthening measure aiming to minimize the mass. The theoretical calculation results show that the static intensity and stability under atmosphere pressure of the optimum scheme can meet the requirements. Subsequently, the inertia supporting framework which connects the bearing unit to the rotor is particularly considered. The framework is constructed by some spokes in order to minimize the mass. And the spokes should be angled relative to the mounting plane for enhancing mechanical capabilities. Then the dimensions and angle of the spokes are optimized due to volume constraints and so on. Finally, a prototype of a compact mechatronic wheel currently under constructions is presented. It's shown that the designed system has good performance during the whole process of the qualification tests. So it is approved practically that the proposed flywheel is available to miniature satellites. [View Full Paper]

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STATION-KEEPING STRATEGY OF DFH-4S PLATFORM SATELLITE WITH ELECTRIC PROPULSION

LYU Nan,* HU Shaochun,† CUI Zhenjiang‡ and PENG Weifeng§

DFH-4S (DFH-4 Small and Smart) Platform is a medium capacity geostationary orbit(GEO) common platform, it is the first Chinese GEO Satellite Platform that adopts electric propulsion system(EPPS). ChinaSat-16 is the first full configuration satellite on DFH-4S platform, it is equipped with four 40 mN Li-ion thrusters for north-south station-keeping(NKKS), meanwhile several 10N chemical thrusters are adopted for east-west station-keeping(EWSK) and 3-axis attitude control. The stationary position of ChinaSat-16 is 110.5°E, a station-keeping strategy was developed and simulated considering satellite orbit accuracy, ground operator convenience and propellant consumption, the design result shows that the strategy can satisfy the requirement of satellite flight mission. ChinaSat-16 was launched on Apr 12,2017 successfully, the station-keeping strategy has been applied in the in-orbit operation. An overview of DFH-4S platform station-keeping strategy is given in this paper. [View Full Paper]

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RESEARCH ON PRECISE TORQUE CONTROL FOR THE MAGNETICALLY SUSPENDED FLYWHEEL IN TORQUE CONTROL MODE

LIU Qiaolin,* LIU Kun† and FENG Jian‡

The magnetically suspended flywheel is used as torque executive component in satellite attitude control system, which has the features of high control accuracy, low vibration noise and long life. In order to realize the high-accuracy of torque output of the magnetically suspended flywheel, the design of torque control mode and PWM modulation are improved. Aiming at the influence of disturbing torque on the accuracy of output torque of magnetically suspended reaction wheel, the design of speed feedback compensation control is carried out to realize the tracking of the torque instruction. Under the three-phase six-state control mode, the commutation torque ripple exists in the brushless DC motor, and the electromagnetic torque ripple is changed with different PWM (pulse width modulation) modes. Based on five PWM modes used in BLDCM (brushless DC motor) control system. The relationship between commutation torque ripples and PWM modes are discussed. The simulation results prove that the commutation torque ripples will be the smallest when the PWM-ON mode is used in satellite attitude control system. At the same time, a new control strategy based on RBF neural network PI algorithm is proposed. Compared with traditional PI controller, this approach has quicker response speed and better robustness, which can achieve high-precision tracking of the torque instruction. [View Full Paper]

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ATTITUDE CONTROL OF UNDER-ACTUATED SPACECRAFT WITH TWO REACTION WHEELS BY ROTATING THE SOLAR PANELS

Yingjie Li and Lei Jin*

This paper describes a novel attitude control strategy for an under-actuated spacecraft with two RWs (Reaction Wheels), using the active assistance of SRP (solar radiation pressure) torque. In this case, the magnitude and direction of the solar radiation pressure torque can be adjusted by changing the solar panel rotation angles. The model is linearized and the linear quadratic regulator (LQR) controller is designed to obtain the command control torque. The numerical solution is used to calculate the windsurfing angle to provide the expected torque along under-actuated axis. The simulation results prove the effectiveness of this control method. [View Full Paper]

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A HIGHLY RELIABLE FOUR-FOV STAR SENSOR MODULE

Hao-ran Ji[*] and Guo-qiang Zeng[†]

The star sensor is a kind of high-precision attitude sensor, however, complex optical environment in space restricts its reliability. Multi-field-of-view star sensors have higher reliability in attitude determination than traditional single-field-of-view star sensors. In this paper, a new type of four-field-of-view (four-FOV) star sensors module is proposed, under which the pixel planes of four light-sensitive elements compose a regular tetrahedral framework. The module appears a frustum of a triangular pyramid, makes it volume saving and can be installed efficiently and accurately. The reliability probability of this kind of module at different orbit altitudes is calculated, based on a theoretical mathematical model. Simulation results show an advantage in reliability of the regular tetrahedral four-FOV star sensor module.

Keywords: Star sensor; High reliability; Four-field-of view configuration; Regular tetrahedral framework. [View Full Paper]

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DESIGN OF OPTICAL SYSTEM FOR SUN SENSOR WITH BIREFRINGENCE IN UNIAXIAL CRYSTAL

Yanli Li,[*] Dong Gao[†] and Deng Pan[‡]

In this paper, the birefringence sun sensor which based on birefringence of uniaxial crystal is proposed for the first time. There are two exit rays when the sunlight passes through the birefringence sun sensor. By calculating the coordinates of two exit rays on the APS surface, not only the pitch and yaw information but also roll information of the sun sensor relative to the sun are obtained. The designed optical system is composed of an APS CMOS image sensor, a pinhole imaging system and calcite. On the basis of Huygens' theory, a digital sun sensor imaging model combining pinhole imaging with uniaxial crystal was constructed. Based on the birefringence theory of uniaxial crystal, an optical system simulation model was established on computer. The parameters of aperture, uniaxial crystal size and spacing between optical axis and uniaxial crystal were designed, and the numerical simulation was carried out. The results indicate that the uniaxial crystal sun sensor with birefringence can realize the three-dimensional measurement of the attitude, and has the characteristics of high precision and large field of view.

[View Full Paper]

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RESEARCH ON THERMAL CONTROLLED PROTECTION COATING OF LOW ORBIT SPACE-BORNE ANTENNA

Yafeng Wang,[*] Jianghua Hu,[†] Yan Wang,[‡] Lian Liu[§] and Hui Yang[**]

Space environment is very complicated. Spacecraft will be intensively effected by different space environment factors. Low orbit space-borne antenna belongs to externally mounted equipment and its surface temperature is influenced by external heat source, such as sun. Thermal control protection coating of passive thermal controlled technology is always applied to adjust thermal radiation properties of the solid surface in spacecraft and aim to control the temperature. The object of this study is the low orbit space-borne antenna. The thermal controlled protection application requirements in space is the main research contents. The functional coating is manufactured by ion beam assisted vacuum coating technology. A series of tests are performed to validate the characteristics of the protection coating. The influences of coating thickness to hemispherical emittance, the influences of substrate surface to solar absorptance, film adhesion, high temperature resistance performance, anti-atomic oxygen performance, and resisting ultraviolet radiation property are analyzed by different experiments. The thermal controlled protection coating technology provides implemented foundation of the space-borne antenna.

[View Full Paper]

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THERMAL ANALYSIS OF SUN SHIELD AND MULTI-LAYER COMPOSITE ADIABATIC STRUCTURE FOR CRYOGENIC TANKS

Jiazheng Song, Yiyong Huang and Zongyu Wu*

With the development of deep space exploration, especially future manned lunar exploration program, cryogenic propellant (such as hydrogen and oxygen, methane etc.) has been widely used on the rocket owing to its advantages of high specific impulse and no pollution. However, the complex space thermal environment the spacecraft suffers on orbit (e.g. the solar radiation, the earth's infrared radiation, the earthlight, the space background etc.) brings the great difficulties in the long-term storage of cryogenic propellants. The multi-layer insulation (MLI) is usually used to prevent the leakage of ambient heat into the tank, but it often requires tens of or even hundreds of layers to meet the design demand. To solve the above problems, a cryogenic propellant low evaporation storage scheme combining sun shield and MLI is put forward, and a mathematical model of heat transfer outside the cryogenic propellant tank is established. The variable condition analysis is carried out to reveal the effects on the thermal isolation of the proposed scheme put by different factors, including the area ratio of sun shield and MLI, the distance between sun shield and satellite and the number of sun shield. The temperature field of different schemes is numerically simulated and studied. Through comparative analysis, it was found that compared with the MLI adiabatic scheme, when the multilayer insulation material in the SS-MLI scheme had only 15 layers, the adiabatic performance was better than that of the 50 layer insulation material in the MLI model. At this time, the heat leakage was only 8.65W. The daily evaporation rate of the low-temperature tank is only 0.32%. The cryogenic tank has a small heat leakage and has a good thermal insulation effect. The theoretical basis is laid for further research on the long-term on-orbit storage scheme design and optimization. [View Full Paper]

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RESEARCH ON FAULT PROGNOSTIC FOR SLIP RING IN CONTROL MOMENT GYROSCOPE

Wenshan Wei,[*] Lei Zhao,[†] Baichen Zhai,[‡] Jintao Wu[§] and Dengyun Wu[**]

Slip ring in Control Moment Gyroscope (CMG) is a crucial part that provides the continuous power supply and signal transmission for spin motor and the angle measurement unit. A sudden interruption of the slip ring will lead to the abnormal operation of the CMG and even impact the satellite. Extra sensor and high sampling rate are both required in the existing method for slip ring monitoring and prognostic. In this paper, the random forest method is introduced to monitor and predict the slip ring fault with ultralow sampling rate of 8Hz. Experiment result reveals the validity of the random forest method since its high accuracy over 99%. Furthermore, four most informative variables are identified by mean decrease in accuracy and Gini index, with which a reduced model is sufficient to maintain the performance. [View Full Paper]

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A NEW GYROSCOPIC PRINCIPLE. NEW GYROSCOPIC EFFECTS ON COLD ATOMS AND ON DE BROGLIE WAVES, DIFFERENT FROM THE SAGNAC EFFECT

Nikolay I. Krobka*

The works of the Scientific Research Institute for Applied Mechanics named after Academician V.I. Kuznetsov are presented. This paper provides a brief overview of the state-of-the-art development of a new generation of inertial sensors on cold atoms for space applications. The problem of narrowing the dynamic range of atomic interferometers in comparison with optical interferometers and method for resolving this problem are discussed. Three new results are presented for the first time: 1) A new "kinematic" gyroscopic principle that allows one to uniquely determine the absolute angular velocity without limitations on the measurement range, in contrast to the interferometric gyroscopic principle; 2) Rigorous expressions of gyroscopic effects on cold atoms and on de Broglie waves on kinematic and interferometric gyroscopic principles, which are fundamentally different from the Sagnac effect; 3) The asymmetry of the particle-wave duality seen in gyroscopy: an increase in the sensitivity to rotation when stepping from photons to atoms is colossally greater than the increase in sensitivity when stepping from light waves to de Broglie waves of the order of $(10^{13} \div 10^{7})$ at atom temperature of the order of $(10^{-9} \div 10^{-3})$ K. [View Full Paper]

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RESEARCH ON THE INERTIAL MEASURING METHOD FOR HYPERSONIC VEHICLE BASE ON GFIMU

Ming Yang,* Ming Liu,† Ding Yang,‡ Xiaoli Qin§ and Yajie Ge**

In order to adapt to the high dynamic, high maneuver and large acceleration characteristic of hypersonic vehicle, the gyro-free inertial measurement unit(GFIMU) which use accelerometers instead of gyroscopes to measure the angular velocity of hypersonic vehicle is proposed in this paper. For this program, a twelve-accelerometer configuration scheme is designed and the derivation of linear acceleration, angular acceleration, and angular velocity states from the GFIMU is reported firstly; Then a aided star-sensor based angular velocity calculation approach combining with kalman filter is presented which can effectively avoid the sign ambiguity problem of angular velocity and enhance the accuracy of angular velocity; Lastly, the simulation is carried out and the results show that it can avoid the sign ambiguity problem and has the advantage of even higher acceleration and angular rate solution accuracy, the GFIMU for hypersonic vehicle is available.

[View Full Paper]

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A FAULT DIAGNOSIS APPROACH BASED ON PCA AND DAG-SVM FOR HYDROSTATIC FLUID GYRO PLATFORM SYSTEM

Zhijun Chen,* Langfu Cui,† Qingzhen Zhang‡ and Bo Lu§

Hydrostatic fluid gyro platform systems (called as inertial platform system) are widely applied in missiles and other weapons. Due to the complex structure composition of the inertial platform system, the traditional fault diagnosis methods are difficult to achieve rapid and accurate fault location. In this paper, a new fault diagnosis method based on Directed Acyclic Graph and Support Vector Machine (DAG-SVM) are presented for fault diagnosis. The DAG-SVM fault diagnosis model is established based on the stabilization loop of inertial platform system, and Principal Component Analysis (PCA) method is used to reduce the dimensionality of measured datasets. The multi-class classification model of SVM is trained using the measured datasets of stabilization loop, and these classifiers trained by each two types of the training samples are used as the root node of the DAG to construct a complete fault diagnostic model. Simulation results show that the DAG-SVM fault diagnosis model has higher accuracy in diagnosis, and faster training and testing in velocity. It can achieve better diagnosis results with limited training datasets, which overcomes the problem of model inaccuracy while the traditional neural network trains with the same testing datasets. [View Full Paper]

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ANALYSIS AND CORRECTION METHOD OF STELLAR ABERRATION FOR HIGH-RESOLUTION SATELLITES

WU Jingyu,[*†] JIA Yansheng,[*†] ZHONG Jinfeng,[*†] WANG Yanqing,[*†] WAN Yabin[*†] and GUO Siyan[*†]

With the development of high resolution satellites, it requires to improve the control accuracy and image positioning accuracy. The attitude determination is one of the most critical problems, star sensor is now the most precise attitude measurement instrument, which plays an important role in attitude measurement and control system. The measurement error has a great impact on the satellite attitude determination accuracy. This paper analyzes the principle of stellar aberration, derives the aberration error angle, which is used to correct the output of the star sensor. Onboard results show that the proposed onboard correction method of stellar aberration can improve the satellite attitude determination accuracy. [View Full Paper]

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