Abstract

論文の内容の要旨

Optimal Attitude and Orbit Control of a Spinning Solar Sail by Spin Rate Control

（スピンレート制御によるスピン型ソーラーセイルの最適姿勢・軌道制御）

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Solar sails are a form of spacecraft which deploys a large sail in space and uses solar radiation pressure for propulsion. Solar sailing is considered as an ultimate propulsion system since it does not require any propellant. In 2010, IKAROS developed and launched by Japan Aerospace Exploration Agency (JAXA) has become the first solar sail spacecraft in the world [1, 2]. IKAROS successfully achieved its objective to demonstrate various novel technologies regarding solar sailing: the deployment of a 200 m^2 sail, power generation with thin-film solar cells on the sail, measurement of acceleration due to solar radiation pressure, and guidance and control of a solar sail spacecraft in interplanetary space. NASA also launched a solar sail spacecraft called NanoSail-D2 into a low Earth orbit in 2010 [3]. IKAROS and NanoSail-D2 are to be followed by several solar sail projects. The importance of solar sailing is widely acknowledged, and solar sails are being as popular as ever.

This thesis deals with a spinning solar sail in interplanetary space. In general, spinning solar sails are considered to have a good prospect compared to three-axis stabilized solar sails. This is because the fact that spinning solar sails do not require such rigid structures as booms or masts leads to weigh reduction. This is a critical criterion for solar sails since a high sail area-to-mass ratio is necessary to use solar radiation pressure for propulsion.

In past Japanese deep space missions including IKAROS, it was shown that the spin-axis direction of a spinning spacecraft rotates around an equilibrium direction near the Sun direction due to the effect of solar radiation pressure [4, 5]. This phenomenon is called an “attitude drift motion”. It is known that this attitude motion can be controlled by the spin rate of the spacecraft. The solar radiation pressure force on the sail, hence the acceleration gained by the solar sail, is dependent on

the attitude with respect to the Sun. The orbit of a spinning solar sail can be, therefore, controlled indirectly by the spin rate through the attitude drift motion. In this thesis, the attitude and orbit control of a spinning solar sail by the spin rate is proposed.

The significance of this research is that a pure under-actuated system is investigated. The six degrees of freedom of the attitude and orbital motions are controlled by single control input, which is the spin rate. In other words, the attitude and orbit of a spinning solar sail is controlled by a minimum control degree of freedom. The control strategy proposed in this thesis provides ultimate redundancy and simplicity for a spinning solar sail because it enables the guidance and control of the spacecraft provided that only the spin rate is controllable.

In previous work, it is shown that the orbit control by the spin rate is feasible to be applied in some cases [6, 7, 8]. It is, however, limited to very specific problems, such as the guidance and control of IKAROS to the sphere of influence of the Earth or Venus. On the other hand, the objective of this thesis is to determine spin rate control laws for more general problems of attitude and orbit control of a spinning solar sail. An approach taken in this thesis is to solve optimal control problems for several different purposes analytically, and to perform numerical analyses in order to prove the validity of the analytical derivation. The direct collocation with nonlinear programming method is used for the numerical analyses [9, 10]. The work in this thesis is divided into the following chapters.

Chapter 2. Attitude and Orbit Dynamics Models

In this chapter, dynamics models that are used in this thesis are introduced, and equations of attitude and orbital motions are shown. With regard to the attitude motion of a spinning solar sail, equations of the attitude drift motion are derived to demonstrate the rotational motion of the spin-axis direction around an equilibrium direction. The equations show that the attitude drift motion can be controlled by the spin rate. The orbital motion of a spinning solar sail is calculated using the two-body problem in this thesis. Equations of orbital motion including solar radiation pressure are shown.

Chapter 3. Acceleration and Deceleration Manoeuvres

As the most fundamental orbit control manoeuvres, optimal spin rate control laws to accelerate and decelerate a spinning solar sail are derived by optimising the attitude drift motion. Optimal control problems are formulated with cost functions of solar radiation pressure acceleration to maximise the acceleration and deceleration in the transverse direction. Analytical derivations and numerical analyses prove that simple bang-bang control of the spin rate is optimal as acceleration and deceleration manoeuvres [11].

Chapter 4. Orbital Elements Optimisation

Orbital elements are optimised in this chapter. Optimal spin rate control laws for orbital inclination maximisation, orbital eccentricity maximisation, aphelion maximisation and perihelion minimisation are determined. In every problem, a locally optimal trajectory is determined by optimising the attitude drift motion analytically, and it is followed by a numerical optimisation to determine a globally optimal trajectory and to prove the validity of the analytical solution.

Chapter 5. Exact Linearisation of Bilinear System for Attitude Control Manoeuvres

In this chapter, nonlinear equations of the attitude drift motion are linearised using a method called “exact linearisation". It is a method to transform a nonlinear system into an equivalent linear system using a coordinate transformation and state feedback. The effectiveness of the exact linearisation is demonstrated by formulating an optimal control problem of attitude control manoeuvres that is analytically solvable. Since the attitude drift motion can be controlled by the spin rate, attitude control can be performed by controlling the spin rate and using the attitude drift motion. An optimal spin rate control law to perform attitude control is determined analytically [12].

Chapter 6. Circular Orbit-to-Circular Orbit Transfer Optimisation

The exact linearisation is used to linearise equations of the attitude drift motion, and its effectiveness is proved with example attitude control manoeuvres in the previous chapter. In this chapter, on the other hand, orbit control of a spinning solar sail using the exact linearisation is investigated. Exactly linearised equations of the attitude drift motion are combined with the equations of orbital motion. The attitude and orbital motions are dealt with analytically simultaneously, and globally optimal trajectories for a circular orbit-to-circular orbit transfer are determined. It is assumed that a spinning solar sail is initially in a circular orbit in the ecliptic plane with a radius of 1 AU, and it is transferred to another circular orbit with a larger radius.

Spin rate control laws for optimal attitude and orbit control are determined in this thesis. Analytical and numerical analyses are performed to solve optimal control problems for acceleration and deceleration maximisation, orbital elements optimisation, attitude control optimisation and circular orbit-to-circular orbit transfer optimisation. The significance of this research is that a pure under-actuated system is investigated. The six degrees of freedom of the attitude and orbital motions are controlled by single control input, the spin rate. It provides ultimate redundancy and simplicity for a spinning solar sail because it enables the guidance and control of the spacecraft provided that only the spin rate is controllable. The control strategy proposed in this thesis, therefore, greatly contributes to the guidance and control of future spinning solar sails.

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