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Author: Mr. Zhan Feng
School of Astronautics, Beihang University, China

Dr. Xingji He
Yunnan Police College, China
Dr. Tao Nie
School of Aerospace Engineering, Beijing Institute of Technology, China
Prof. Ming Xu
School of Astronautics, Beihang University, China

APPROXIMATE ANALYTICAL SOLUTION TO SPACECRAFT OPTIMAL DOCKING USING KOOPMAN OPERATOR THEORY

Abstract

Spacecraft docking requires relative motion to meet equality terminal constraints and inequality path constraints, such as the transverse position, transverse velocity, approximate speed, and collision avoidance. Therefore, the minimum-energy control strategy of docking is an optimal control problem (OCP). Traditionally, numerical methods are used to solve such OCPs. However, the numerical integration errors and large optimization size cause the computation time too large. To reduce the computational burden, this work proposed an approximate analytical solution to the docking problem using the Koopman operator and saturation function.

Firstly, the inequality-constrained OCP is transformed into an equality-constrained one by the saturation function, where the inequality path constraints are substituted by the saturation function of new variables. Secondly, the two-point boundary value problem derived from the equality-constrained OCP is solved via the approximation of Koopman operator. To fully describe the system dynamics, the high-order Legendre polynomials are selected as the Koopman basis functions, and Galerkin method is used to construct the eigenvalues and eigenfunctions. Thirdly, the state and costate propagation are expressed as a linear combination of the basis functions, by which a polynomial map is obtained. Then, the map inversion technique is utilized to express the initial value of costate as a polynomial function of the initial and final state, which further yields the approximate analytical solution of the control and state of minimum-energy docking.

Finally, the comparison between the proposed method and traditional numerical methods (e.g., the pseudospectral method) is presented. The simulation results show that on the basis of similar optimal control strategy results, the proposed method significantly reduces the computation time.