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A DATA-DRIVEN NONLINEAR OPTIMAL CONTROL USING KOOPMAN OPERATOR ON HAMILTONIAN FLOW

Abstract

The minimum fuel problem of low-thrust spacecraft in gravitational field is formulated as the nonlinear optimal control problem, and is crucial problem in mission design. In the indirect method to nonlinear optimal control problems, the Hamiltonian system, which is a closed differential equation with respect to the state variables and adjoint variables derived from the necessary condition for optimal control, is solved to satisfy the boundary conditions. In the direct method, the state variables are discretized and the problem is solved as a nonlinear programming, which solves an optimization problem with finite dimensional parameters. Both approaches are solved primarily by iterative computation, although it requires finding a solution for each initial state.

The Koopman operator theory, developed by B.O Koopman in 1931, is a powerful framework for analyzing nonlinear dynamical systems. In this theory, the time evolution of a nonlinear dynamical system can be represented by linear operators in an infinite dimensional function space. In recent years, with the development of data science, it has become possible to approximate the Koopman operator by using a finite-dimensional matrix. The data-driven approximation method of the Koopman operator has been extended to a nonlinear dynamical system with control inputs. In this method a nonlinear dynamical system is represented as a linear dynamics with system and input matrices, and standard linear control theories have been successfully applied in the Koopman operator framework. However, it is known that standard data-driven based algorithms do not provide a good approximation of the controlled dynamics and data-driven control laws do not work well.

In this study, we propose a new method to solve the nonlinear optimal control problem leveraging the Koopman operator on Hamiltonian flows. Instead of applying the data-driven modelling technique to the time-series data of the original nonlinear dynamical system with control input, we apply the technique to the Hamiltonian flow along the optimal control problem. Since the Hamiltonian flow does not explicitly include control inputs, it can improve the problem of previous studies. Then a simple method to solve the nonlinear optimal control problem satisfying the boundary conditions is proposed by computing the state transition matrix of the linear model obtained by the data-driven modelling. This method is an innovative approach that allows us to solve the nonlinear optimal control problem by exploiting the data-driven Koopman operator framework.