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APPLICATION OF NEURAL ORDINARY DIFFERENTIAL EQUATIONS TO TRAJECTORY CONTROL LAWS FOR LUNAR LANDING

Abstract

This paper proposes a new method of applying neural ordinary differential equations (ODEs) to spacecraft trajectory control laws. Neural ODEs are deep learning operations defined by the solution of an ODE proposed by Chen *et al.* (2018). They introduced a family of deep neural network models which utilizes the derivative of the hidden state instead of specifying a discrete sequence of hidden layers in neural networks. One of the useful applications of neural ODEs is learning continuous dynamics. Given a time series of trajectory states in some unknown dynamical system, neural ODEs can be trained to estimate the internal parameters of the dynamical model that can be treated as a black box and reproduce the trajectories. The neural network takes the initial conditions as input and computes the ODE solution through the learned neural ODE model. In the learning of dynamics by the neural ODE model, the ODE that defines the model is solved numerically with the Runge-Kutta method. The difference between the given trajectory state and the result of trajectory propagation by the neural ODE is defined as a loss function, and the gradient of the loss function with respect to the learning parameters is calculated using automatic differentiation. Based on the computed gradient information, the network is trained to minimize the loss function. An example of an algorithm for minimizing the loss function is the adaptive moment estimation algorithm (2014). In this study, we extend this mechanism to design control laws for trajectory control. In the previously mentioned applications, the parameters that can be learned are those related to the equations of motion that define the dynamics. By adding control input terms to the equations of motion and selecting parameters related to the control input as learning parameters, a mechanism to calculate the control input from the trajectory state can be constructed. In particular, the proposed mechanism is applied to the construction of trajectory control laws for lunar landing. The effectiveness of the proposed method is verified by constructing control laws to fulfill the conditions for safe landing under the initial conditions before landing. The proposed method offers various advantages including the possibility of constructing robust control laws that achieve the objective in any state without relying on a reference trajectory, in contrast to conventional control methods, which require the spacecraft to follow a reference trajectory, making it difficult to recover from deviations from the reference trajectory.