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STABILITY ANALYSIS OF GUIDANCE AND CONTROL NETWORKS THROUGH DIFFERENTIAL ALGEBRA

Abstract

Guidance and Control Networks (G&CNETs) are emerging as a promising type of neural network for enhancing onboard autonomy and seamlessly incorporating optimality principles into spacecraft. They provide an alternative to conventional model predictive control schemes (MPC) by leveraging advancements in machine learning. Yet today, neural networks are still seen as inscrutable algorithms, sometimes referred to as "black boxes". With the increasing demand for spacecraft autonomy, it is necessary to develop methods that can assess the robustness of Guidance & Control Networks, akin to stability analysis in control theory. This paper proposes the use of high-order Taylor expansions of the neural flow, for example, computed via Differential Algebra (DA) or equivalent techniques, as a tool to gain insights into the stability of such networks and potentially further tune their parameters. The establishment of so-called High Order Taylor Maps (HOTMs) for such a flow, allows one to describe analytically, for example, the terminal conditions acquired as a function of selected control parameters including initial conditions or other uncertainties, thereby allowing to peek into the stability of the system around a nominal trajectory. We study two complex optimal control problems with different time scales and objectives. The first problem is a time-optimal, low-thrust interplanetary transfer targeting a generic Earth rendezvous starting from the asteroid belt. The transfer time here is in the order of years and the G&CNET learns the optimal thrust direction. The second problem is a mass-optimal landing on the asteroid Psyche. In contrast to the first problem, the landing time is in the order of hours and the network needs to learn both the optimal thrust direction and throttle. For both problems, we derive rigorous bounds on the stability of the resulting neurocontrolled trajectories and study how improving the precision of the trajectories affects these bounds. The accuracy of G&CNETs can be substantially improved with a novel method that makes use of Neural Ordinary Differential Equations (Neural ODEs) sensitivities to network parameters. The sensitivities are computed with the variational equations, or Pontryagin's adjoint method, to inform a gradient descent algorithm that updates the network parameters. Our work highlights both how the

stability of such networks can be assessed and improved, offering a considerable advancement that boosts trust in the fidelity of G&CNETs.