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NeuralExplorer: State Space Exploration of Closed Loop Control Systems Using Neural Networks

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The recent improvements in software and hardware platforms for training and evaluation of neural networks have made it easier to integrate them in embedded devices, but at the expense of software complexity in control tasks. This makes testing and validation of the closed loop systems very challenging. In a typical testing-based work flow, after designing the feedback function, the control designer generates a few test cases for the closed loop system and checks if they satisfy the specification. However, finding a trajectory of interest using testing in continuous state space is similar to searching for a needle in the haystack. In contrast, falsification tools are particularly geared towards finding a trajectory that violates the given temporal logic specification, not necessarily helping the control designer in state space exploration.

While simulation-based verification techniques aim to compute an over-approximation of the reachable set by computing upper bound on the sensitivity of sample trajectories, the number of trajectories generated may grow exponentially with the dimensions. What the control designer needs is a tool that helps them to systematically generate trajectories. In this work, we propose *NeuralExplorer*, a framework for performing state space exploration of closed loop control systems using inverse sensitivity. Informally, sensitivity of a closed loop system is the change in the trajectory of the system as a result of perturbing the initial condition. We introduce a backward time notion of sensitivity called *inverse sensitivity*, i.e., the perturbation of the initial condition that is required in order to produce a desired effect in the trajectory. We present a mechanism for approximating inverse sensitivity by a neural network. This neural network is then used for generating trajectories that reach a destination (or a neighborhood around it).

Our framework has two main advantages. First, since NeuralExplorer relies only on the sample test cases, it does not require a model of the system and can be applied to a black-box system. Second, inverse sensitivity being a fundamental property of the closed loop system, approximating it using a neural network is generalizable to trajectories that are beyond the test cases generated by the control designer. With this framework, we are able to perform state space exploration for standard benchmarks of nonlinear dynamical systems, nonlinear hybrid systems, and neural network based feedback control systems. In all of the benchmarks, the domain of state space considered is at least one or two orders of magnitude larger than a typical reachable set and falsification methods(in volume). Additionally, our approach does not suffer from high computation time incurred due to either slight change in the initial set or lack of generalization. Our technique is capable of achieving below 10% relative distance in almost all cases after a few iterations. We believe that NeuralExplorer is useful for generating corner cases and supplements some of the existing testing procedures.