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FLIGHT DEMONSTRATION OF LIE-GROUP BASED NONLINEAR OPTIMAL CONTROL FOR A VEHICLE WITH ATTITUDE DYNAMICS (LIEQR)

Abstract

Many spacecraft require 6 degree of freedom (6-DoF) guidance of a vehicle with significantly nonlinear and underactuated dynamics. These include planetary probes, landing boosters, or winged reentry vehicles. This paper presents a novel algorithm for 6-DoF guidance, and flight tests on a jet-powered vertical-takeoff and landing (VTOL) vehicle.

Nonlinear and underactuated systems are often controlled by optimal controllers, which optimize over future states and control actions to find a sequence of control actions which will minimize some cost. One popular and robust method for computing such a sequence of control actions is the Linear Quadratic Regulator (LQR), which can be used to generate an optimal trajectory, and a feedback policy at each state. LQR, however, is limited to linear systems with quadratic costs. The Iterative Linear-Quadratic Regulator (ILQR) extends LQR to nonlinear systems, by iteratively computing an LQR solution using a linear approximation of dynamics, and a quadratic approximation of cost. ILQR is limited to systems whose state spaces are also vector spaces. This excludes systems with orientation states, like boats, spacecraft and robotic arms. Our novel algorithm, LieQR, exploits the fact that orientation states are members of Lie groups, which are well-understood objects in mathematics. LieQR applies techniques that have become commonplace in computer vision to extend ILQR to systems with orientation and costs/constraints on orientation. It does so by computing the feedback policies and jacobians in the *tangent space* of the states, which enables the use of well-proven strategies like LQR on systems with orientation, while not being vulnerable to the singularities in vector-representations of orientation.

We also present a tool which easily generates LieQR code for arbitrary systems. Typically, implementing efficient ILQR code requires tedious and error-prone derivations. Our code generation tool sidesteps this issue. Given a high-level specification of the system dynamics, it automatically generates an efficient real-time C++ implementation of LieQR.

To demonstrate this algorithm, we built a jet-powered VTOL vehicle. Our vehicle is steered by thrust-vector control, replicating the key dynamics of many powered landing planetary probes or rocket boosters. Our vehicle is robust to impacts and cheap to repair (many of the parts are 3D printed) making it an ideal guidance and controls testbed. All control software runs onboard the vehicle on an embedded processor (ARM Cortex A-15). We are currently conducting powered hop tests on the vehicle, and will have flight test results for the IAC paper submission.