

Trajectory tracking control design for autonomous helicopters using a backstepping algorithm

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Abstract

In this paper we present a tracking controller for a class of underactuated mechanical systems, based on a backstepping procedure. This class includes an approximation of small helicopter dynamics. The need to avoid artificial singularities due to the attitude representation is the main driver behind the control design presented in this paper: to achieve this goal, we will operate directly in the configuration manifold of the vehicle. The control design provides asymptotic tracking for an approximate model of small helicopters, and bounded tracking when more complete models are considered. Simulation examples, including both point stabilization and aggressive maneuver tracking, are presented and discussed.

1 Introduction

In the recent past, the design and implementation of control algorithms for autonomous helicopters has been the object of a relevant body of research, due to an identified need for maneuverable autonomous aerial vehicles, for both military and civil applications. While slower and less fuel-efficient than airplanes, helicopters are capable of vertical take off and landing, hover, and in general are more maneuverable in tight spaces than airplanes. As a consequence, helicopters are one of the best platforms for operations in urban or otherwise cluttered environments. However, in many respects the dynamics of a helicopter are more complicated than the dynamics of a fixed wing aircraft: a helicopter is inherently unstable at hover, and the flight characteristics change dramatically over the entire flight envelope.

In recent papers, feedback linearization techniques have been applied to helicopter models. The main difficulty in the application of such techniques is the fact that, for any meaningful selection of outputs, the helicopter dynamics are non-minimum phase, and hence are not directly input-output linearizable. However, it is possible to find good approximations to the helicopter dynamics such that the approximate system is input-output linearizable, and bounded tracking can be achieved [1, 2]

The feedback linearization approach suffers from the fact that, since the attitude is parameterized using Euler angles, singularities arise when performing some maneuvers, such as loops, barrel rolls, split-s's etc. A possible solution to the singularity problem is represented by chart switching when approaching a singularity. However, this can be cumbersome in implementation, and can lead to excessively high gains in the proximity of singularities.

On the other hand, the singularities arising in these models are artifacts due to the choice of the attitude parameterization (Euler angles), and do not reflect any intrinsic characteristic of the helicopter dynamics. The need to avoid artificial singularities due to the attitude representation is the main driver behind the control design presented in this paper: to achieve this goal, we will operate directly in the configuration manifold of the helicopter. The "tracking on manifolds" problem was solved in [3] for fully actuated mechanical systems: in this paper we present an extension, for achieving asymptotic (locally exponential) tracking of trajectories for a particular class of underactuated mechanical systems. An approximate model of helicopter dynamics can be shown to be in this class: the approximation that will be used in the paper is the same one that leads to feedback linearizability, or differential flatness of the model. However, the method presented here can deal without any modification with more accurate models, including for example simple aerodynamic forces.

The control design will be based on a non-trivial extension of backstepping ideas [4] to dynamic systems on manifolds. In its basic form the backstepping procedure is carried out on a chain of integrators (integrator backstepping); in our case the backstepping procedure is implemented on a dynamic system evolving on the group of rotations in the three-dimensional space $SO(3)$. A backstepping approach for control of underactuated, non-minimum phase nonlinear systems was used in [5] for control of surface vessels: our problem is more difficult since we need to control the rigid body motion in the three-dimensional space, as opposed to the plane. At the time of writing this paper, the authors also became aware of the work in [6], where a backstepping procedure was implemented to design a controller for a helicopter close to hover. However, the approach in the above paper is still partially based on

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