Robust Optimal Control for Nonlinear Systems with Parametric Uncertainties via System Level Synthesis

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Abstract— This paper addresses the problem of optimally controlling nonlinear systems with norm-bounded disturbances and parametric uncertainties while robustly satisfying constraints. The proposed approach jointly optimizes a nominal trajectory of the nonlinear system and an error feedback, requiring minimal offline design effort and offering low conservatism. This is achieved by reformulating the uncertain nonlinear system as an uncertain linear time-varying system accounting for linearization errors, additive disturbances, and parametric uncertainties. This decomposition enables the application of established tools from system level synthesis to convexly over-bound all the uncertainties online, leading to a tractable nonlinear optimization problem. With this novel controller parameterization, we can formulate a convex constraint to ensure robust performance guarantees for the nonlinear system. The presented method is relevant for numerous applications related to trajectory optimization, e.g., in robotics and aerospace engineering. We demonstrate the performance of the approach and its low conservatism through the simulation example of a post-capture satellite stabilization.

I. INTRODUCTION

A. Motivation

Robust nonlinear optimal control addresses a ubiquitous challenge in various safety–critical applications, such as drones, spacecraft, and robotic systems [1]–[4]. These systems are complex and difficult to model accurately due to uncertainties from measurement errors, unmodeled dynamics, or environmental disturbances. As a result, there is often a mismatch between the predictive model and the actual system. It is therefore crucial to guarantee robust constraint satisfaction to ensure the safety of these systems. However, achieving such guarantees often comes at the cost of conservatism, non-trivial system-specific design, or substantial computational effort (either online during operation or offline during controller design), originating from trading-off performance, robustness, and flexibility, as evidenced by a wealth of prior research on the topic outlined below.

B. Related Work

Traditionally, robust optimal control has been divided into two main steps: (1) the optimization of a nominal trajectory (also called reference trajectory, guidance, or feed-forward) [5] and (2) the offline design of a stabilizing feedback (controller) to compensate for modeling errors

or disturbances. The propagation of those uncertainties is commonly approximated using tubes, funnels [6], and the corresponding reachable sets around the nominal trajectory are used to ensure robust constraint satisfaction. However, this separation may introduce significant conservatism and limit the controller's performance. In this work, we propose an approach that addresses the limitations of this classic design paradigm by considering joint optimization of the nominal trajectory and error feedback, with a focus on robust constraint satisfaction in nonlinear systems with disturbances.

Specifically, this work aims to tackle the challenges associated with a particular class of disturbances: parametric uncertainties, which commonly arise from model mismatch. Techniques for addressing such uncertainties have been developed in the context of robust model predictive control (RMPC). Here, a trajectory optimization problem is solved at each time step, incorporating a fixed feedback and tightened constraints. The conservatism of the constraint tightening is well-studied for linear systems [7]–[9]; however, extending it to nonlinear systems with parametric uncertainties remains a significant challenge in general. Although several computationally efficient methods have been proposed, using non-trivial offline designs based on contraction metrics [10]–[12], these approaches often result in system-dependent or conservative designs.

With the aim of reducing conservativeness, system level synthesis (SLS) [13] has been introduced to jointly and convexly optimize the error feedback and nominal trajectory. Because the error feedback is optimized online, the offline system-specific design is reduced, and SLS-based RMPC typically exhibits reduced conservatism [14], [15], especially in the case of parametric uncertainties [16]. While SLS has been extended to nonlinear systems [17]–[19], including a formulation with robust constraint satisfaction [20], none of the previous approaches have considered parametric uncertainties. In this paper, we fill this gap by incorporating the treatment of parametric uncertainties within the SLS framework for nonlinear systems.

C. Contribution

We present a novel approach for jointly optimizing an error feedback and nominal trajectory for a nonlinear system with parametric uncertainties while ensuring robust constraint satisfaction. Our approach leverages SLS to *convexly* over-bound *online* the disturbances arising from parametric uncertainties and linearization errors, while also addressing additive disturbances. This presents an advantage over [20],

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Table of Contents Synthesis Of Optimal Nonlinear Control Systems

1. Understanding the eBook Synthesis Of Optimal Nonlinear Control Systems
     - The Rise of Digital Reading Synthesis Of Optimal Nonlinear Control Systems
     - Advantages of eBooks Over Traditional Books
2. Identifying Synthesis Of Optimal Nonlinear Control Systems
     - Exploring Different Genres
     - Considering Fiction vs. Non-Fiction
     - Determining Your Reading Goals
3. Choosing the Right eBook Platform
     - Popular eBook Platforms
     - Features to Look for in an Synthesis Of Optimal Nonlinear Control Systems
     - User-Friendly Interface
4. Exploring eBook Recommendations from Synthesis Of Optimal Nonlinear Control Systems

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