Ph.D. Defense Presentation

Nonlinear Control of Robotic Fish

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Abstract

In the past few decades, robots that propel and maneuver themselves like fish, known as robotic fish, have received substantial attention due to their efficiency, maneuverability, and lifelike features. Their agile locomotion can be partially attributed to their bio-inspired propulsion methods, which range from tail (caudal) and dorsal to paired pectoral fins. While these characteristics make robotic fish an attractive choice for a myriad of aquatic applications, their highly nonlinear, often under-actuated dynamics and actuator constraints present significant challenges in control design. The goal of this dissertation is to develop systematic model-based control approaches that guarantee closed-loop system stability, accommodate input constraints, and are computationally viable for robotic fish.

We first propose a nonlinear model predictive control (NMPC) approach for path-following of a tail-actuated robotic fish, where the control design is based on an averaged dynamic model. Moreover, the bias and the amplitude of the tail oscillation are treated as physical variables to be manipulated and are related to the control inputs via a nonlinear map. A control projection method is introduced to accommodate the inputs constraints while minimizing the optimization complexity in solving the NMPC problem. Both simulation and experimental results on a tail-actuated robotic fish support the efficacy of the proposed approach and its advantages over alternative approaches.

Although NMPC is a promising candidate for tracking control, its computational complexity poses significant challenges in its implementation on resource-constrained robotic fish. We thus propose a backstepping-based trajectory tracking control scheme that is practical, computationally inexpensive and guarantees stability. We demonstrate how the control scheme can be synthesized to handle input constraints and establish via singular perturbation analysis the ultimate boundedness of three tracking errors (2D-position and orientation) despite the under-actuated nature of the robot. The effectiveness of this approach is supported by both simulation and experimental results on a tail-actuated robotic fish.
We then turn our attention to pectoral fin-actuated robotic fish. Despite its benefits in achieving agile maneuvering at low swimming speeds, the range constraint of pectoral fin movement presents challenges in control as it can often inhibit the robot from generating thrust in a direction required for maneuvering. To overcome these challenges and achieve quick velocity maneuvering control, we propose a dual-loop control approach composed of a backstepping-based controller in the outer loop and a fin movement-planning algorithm in the inner loop. Simulation results are presented to demonstrate the performance of the proposed scheme via comparison with a nonlinear model predictive controller.

In practical applications, it is more natural to control the parameters of periodic fin beats than directly controlling the fin position at every moment. To this end, we propose a scaling-based approach to develop a control-affine nonlinear dynamic average model for a pectoral fin-actuated robotic fish, which is validated via both simulation and experiments. The utility of the developed average dynamic model for pectoral fin-actuated robotic fish is demonstrated via the synthesis of a dual-loop backstepping-based trajectory tracking controller.

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