Abstract

The coupling phenomena in industrial systems pose significant challenges to control optimization. These challenges are primarily manifested in the uncertainty, mutual interference, and nonlinearity introduced by coupling effects, which fundamentally alter the structure of the optimization problem. As a direct consequence, both the real-time performance and the accuracy of industrial optimal control are often compromised. To address these challenges, the following key questions must be answered: What are the principal forms of industrial coupling? What are the characteristics of each form? How do these characteristics affect optimal control problems? Ultimately, how can optimal control still be achieved under these influences?

To answer these questions, this thesis first classifies industrial coupling problems in Chapter 2. Adopting a macro-to-micro perspective, industrial coupling is categorized into: (a) coupling between the industrial system and its environment, (b) coupling among internal components of the system, and (c) coupling between the system and the working medium. The characteristics of each coupling type and their potential impacts on optimal control problems are systematically analyzed. Achieving optimal control under such coupled conditions necessitates appropriate modeling. Therefore, we propose a Model-assisted Optimal Control Framework for Industrial System Coupling Problems.

Building upon this framework, we selected three representative industrial applications as case studies for the three coupling scenarios. First, in the second part of this thesis (Chapter 3), the trajectory planning problem for Tunnel Boring Machines (TBMs) is investigated as a case of system-environment coupling. During operation, a TBM interacts continuously with the surrounding geological environment, yet the unmeasurable nature of subsurface conditions introduces significant uncertainty into control decisions. To address this, we examine how to achieve accurate trajectory guidance under partially observable conditions, implementing precise inference and decision-making through a fragmented modeling approach. In the third part (Chapter 4), we study reflow soldering temperature profile control as a typical example of coupling among subsystems within an industrial system. In a reflow oven, heating zones interact with each other, making control parameter optimization a representative challenge of this coupling type. Such interactions cause control parameters to be interdependent, increase the dimensionality of the search space, raise computational costs, and ultimately degrade real-time control performance. By constructing a surrogate-assisted digital twin, we achieve one-shot optimization based on limited samples, effectively mitigating the high computational expense. In the fourth part of the dissertation (Chapter 5), we select the centrifugal compressor as a classic instance of system–working medium coupling. In centrifugal compressor control, capacitive media such as gases and liquids introduce pronounced nonlinearity, manifested as a lagged response of the system to control inputs. To counteract the safety risks arising from this hysteresis, we develop a CMA-ES-based PID controller, which effectively handles the delay-induced control challenges.