Model-assisted optimal control framework for industrial system coupling problems

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CHAPTER 1

Introduction

1.1 Background

Industrial systems form the backbone of modern manufacturing, energy production, transportation, and process industries, serving as the essential infrastructure that sustains economic growth and societal development (Xu et al. 2021). These systems encompass a wide spectrum of configurations, ranging from ultra-large tunnel boring equipment and precision manufacturing lines to fluid machinery. Their operational processes are rarely isolated; rather, they unfold within complex physical, chemical, and organizational contexts that require constant coordination across multiple subsystems (Wang et al. 2021).

In practice, the functioning of an industrial system involves intricate interactions among physical components, the working media they process, and the surrounding environment in which they operate. These interactions are governed by multi-physics phenomena—such as thermodynamics, fluid dynamics, structural mechanics, and electromagnetic effects—as well as multi-scale temporal and spatial dynamics (Xing et al. 2024; Kieckhefen et al. 2020, Shahriar et al. 2024). As a result, the system's performance at any given time emerges from a tightly coupled interplay between internal mechanisms and external influences, making its behavior inherently complex, adaptive, and sensitive to disturbances. Taking the tunneling process of a Tunnel Boring Machine (TBM) as an example, during its operation, mechanical, hydraulic, fluid, and thermodynamic systems form a tightly interactive closed loop within the machine: hydraulic systems drive structural components, friction generates heat, and thermal management in turn constrains hydraulic efficiency (Garcia et al. 2021; Mahmoodzadeh et al. 2021). External interactions occur among geology, soil–water conditions, and the machine: geotechnical properties determine loading, groundwater affects pressure equilibrium, and excavation itself perturbs the surrounding strata (Xu et al. 2021; Guo et al. 2022). Ultimately, the overall system performance is determined by the deeply intertwined internal and external coupling—external environmental disturbances penetrate the rock–machine interface, triggering chain reactions across multiple internal fields; meanwhile, internal performance degradation (such as overheating or wear) alters external geological responses through modified machine behavior, resulting in a dynamic, sensitive, and difficult-to-fully-decouple complex adaptive system.

Such coupling phenomena exert a profound influence on the operation and optimal control of industrial systems (Liu et al. 2022; Dang et al. 2022; Gajic et al. 2018). When external environments fluctuate unpredictably, when multiple subsystems are strongly interdependent, or when nonlinear dynamics and time delays arise from interactions with working media, the system's behavior can deviate substantially from the desired operating conditions (Zhang et al. 2017). For control systems, this translates into increased difficulty in maintaining stability, ensuring safety, and achieving efficiency targets. Controllers that assume simplified or decoupled dynamics often perform poorly under real-world conditions, leading to oscillations, degraded product quality, higher energy consumption, or even catastrophic failures (Liu et al. 2023).

The importance of addressing coupling in industrial optimal control lies in its direct impact on system reliability, safety, and competitiveness (Gajic et al. 2018). Without explicitly accounting for coupling effects, a control strategy may lead to ineffective or even failed decision-making. For instance, a controller that ignores environmental uncertainty may become unstable under unexpected disturbances; a design that neglects subsystem interdependencies may lead to bottlenecks or inefficiencies; and a controller that disregards nonlinear medium dynamics may jeopardize operational safety. In all cases, overlooking coupling risks not only suboptimal performance but also severe economic and safety consequences.

Therefore, it is imperative to develop optimization frameworks that explicitly account for coupling phenomena in industrial systems. Such frameworks must integrate accurate system modeling with advanced optimization methods to ensure that solutions remain feasible, robust, and efficient under real operating conditions. This necessity motivates this thesis, which aims to construct a model-assisted optimization framework tailored to industrial coupling problems, thereby bridging the gap between theoretical optimization and practical system performance.

Building upon the model-assisted paradigm, optimization methods must be further refined to explicitly account for different types of coupling phenomena in industrial systems. Rather than adopting a one-size-fits-all strategy, the framework advocates tailored optimization approaches that leverage the strengths of both physical modeling and computational intelligence. Different coupling phenomena necessitate distinct modeling methodologies:

- For industrial systems interacting with their environment, comprehensive modeling requires separate consideration of the industrial system, environmental factors, and their interaction mechanisms to fully characterize their dynamic co-evolution during operation.
- For components coupling within industrial systems, the primary challenge lies in modeling the intricate coupling mechanisms among numerous components, which often leads to prohibitive computational costs—a scenario where surrogate modeling emerges as a viable solution.
- For industrial systems coupled with working media, the modeling approach must fundamentally analyze the energy transfer principles governing these interactions.

By aligning optimization strategies with the specific nature of coupling, this thesis proposed a model-assisted framework by constructing a physically consistent model and improves the optimization algorithm for different optimization scenarios. This synergy of physics-informed modeling and customized optimization forms the central contribution of this thesis.

1.2 Research Questions

In industrial coupling scenarios, it is impractical to apply a single method for once-and-for-all resolution of optimal control problems. Different coupling scenarios must be systematically categorized, and corresponding mechanism models and optimization methods should be developed based on their distinct characteristics. As outlined in the background, industrial coupling problems can be classified into three major categories:

(1) coupling between industrial systems and the environment

(2) coupling among components within industrial systems

(3) coupling between industrial systems and working media (e.g. gas and liquid)

In scenarios involving the coupling between industrial systems and the environment, the core challenge lies in the **frequent inability to directly measure or predict environmental states**. Such uncertainties compromise the reliability of control decisions and diminish the effectiveness of control strategies. Consequently, a key problem to address is the following research question (RQ):

RQ 1： How to mitigate the impact of unobservable environmental states on decision-making and achieve optimal control in partially observable environments.

In the context of coupling among components within industrial systems, the primary challenges arise from the **high dimension of control parameters, the high simulation costs associated with accurately modeling the coupling mechanisms among components within a system,** and **conflicts between locally optimal control parameters and global control objectives due to inter-component interference**. This often leads to suboptimal performance or even failure of optimization processes. Furthermore, the coupling of multiple control parameters expands the dimensionality of the search space, significantly increasing computational costs. The core problem thus lies in the following RQ:

RQ 2： How to achieve accurate optimization of control parameters while avoiding the high computational costs of iterative searches in high dimensional spaces and expensive high-fidelity simulations.

In coupling problems between industrial systems and working media, the core challenge stems from **the diverse physical characteristics of different media-such as energy capacity, compressibility, and flow dynamics-which often introduce nonlinearities into the control process, resulting in control hysteresis**. This time-lag effect can induce oscillatory system states during control execution, leading to operational deviations and safety risks. The fundamental problem to be addressed is the following RQ:

RQ 3: How to design control strategy for nonlinear systems with capacitive working media, capable of eliminating system hysteresis and achieving safe, stable control.

1.3 Outline

The motivation, research content and case study of each chapter are briefly introduced in this part.

Chapter 2 elaborates on the optimization needs in industrial coupling problems, classifies various forms of coupling challenges and their core issues, discusses the role of model-assisted optimization in addressing such problems, and proposes a general solution framework for optimization in industrial coupling scenarios based on model-assisted methodologies.

Chapter 3 addresses the scenario of coupling between industrial systems and the environment, focusing on the issue of partial observability in operational settings. Using TBM trajectory navigation as a case study, a hierarchical partially observable Markov decision process (POMDP) framework is proposed. Through experiments in path planning, thrust prediction, and knowledge transfer, its effectiveness is empirically validated, demonstrating accurate control decision-making under environmental uncertainty.

Chapter 4 focuses on the coupling among components within industrial systems, addressing the optimization challenges under multi-component interaction. Taking the temperature profile design in a reflow furnace as a case study, this chapter proposes a Transformer-Convolutional Neural Networks (Transformer-CNN) based surrogate modeling method for forward-inverse mapping, enabling one-shot optimization. Using data generated from computational fluid dynamics simulations, a high-accuracy surrogate model of the reflow furnace temperature field is established and validated.

Chapter 5 addresses the coupling between industrial systems and working media, focusing on safety control under such interaction. Taking the coordinated control of fluid machinery as an example, this chapter proposes a safety controller based on Covariance Matrix Adaptation Evolution Strategy (CMA-ES), aimed at reducing overshoot during transient coordination and mitigating surge risk. Experiments demonstrate that the proposed control strategy effectively shifts the operating point trajectory of compressors away from the surge region during coordinated control, thereby lowering the risk of instability and surge occurrence.

Chapter 6 summarizes the thesis based on the results obtained from the three case studies. We provide a further discussion on the strengths, limitations, and application constraints of the proposed solutions for three distinct types of industrial system coupling. Furthermore, we outline directions for future work. The chapter also articulates the contributions of the proposed methods to industrial applications and other potential application scenarios, offering guidance for further industrial implementation.

The relationships between chapters are illustrated in Figure 1.1.

1.4 Contributions of this Thesis

This thesis proposes a model-assisted optimization framework for industrial system coupling problems, addressing three categories of coupling - industrial system-environment coupling, coupling among components within industrial systems, and industrial system-working media coupling. Through case studies in TBM trajectory navigation, reflow furnace temperature control, and fluid machinery coordinated control, it examines the core challenges in different industrial coupling scenarios and proposes tailored optimization strategies. By appropriately selecting and integrating auxiliary models, the framework achieves control objectives and enhances control performance. The list of publications by the author during the doctoral period is as follows:

Journal paper:

Xiaohan Wei, Qing Zhang, Thomas Bäck, and Hao Wang. A hierarchical partially observable Markov decision process framework for tunnel boring machine trajectory navigation. *Engineering Applications of Artificial Intelligence*, 166(Part B):113663, 2026.

Qing Zhang, **Xiaohan Wei**, Ye Wang, and Chenggang Hou. Convolutional neural network with attention mechanism and visual vibration signal analysis for bearing fault diagnosis. *Sensors*, 24(6):1831, 2024.

Tingting Jiang, Qing Zhang, Junshen Zhang, and **Xiaohan Wei**. Variational multi-harmonic duality mode pursuit method for extracting repetitive transient components from vibration signals. Measurement, 225:113987, 2024.

Qing Zhang, Tingting Jiang, and **Xiaohan Wei**. Instantaneous speed estimation of induction motor by time-varying sinusoidal mode extraction from stator current. Mechanical Systems and Signal Processing, 200:110608, 2023.

Tingting Jiang, Qing Zhang, **Xiaohan Wei**, and Junshen Zhang. Variational multi-harmonic mode extraction for characterising impulse envelope of bearing failures. *ISA Transactions*, 132:524-543, 2023.

Jin Zhao, Qing Zhang, and **Xiaohan Wei**. An integrated approach of a field-circuit coupling model and multi-physics finite-element simulation for analysing transient electromagnetic vibration of pump motors. *IET Electric Power Applications*, 16(9):1030–1056, 2022.

Conference paper:

Xiaohan Wei, Qing Zhang, Thomas Bäck, and Hao Wang. A Sequence-to-Sequence Multi-Fidelity Surrogate Modeling Approach for the Reflow Soldering Process. In *Proceeding of the 7th International Conference on Robotics, Intelligent Control and Artificial Intelligence, Hangzhou, China, November 14 – 16, 2025,* (pp. 822-826). IEEE.

Paper under review:

Xiaohan Wei, Qing zhang, Wei Ru, Thomas Bäck, and Hao Wang. Surrogate Model–Aided Digital Twins for Multi-Coupling Control Process Parameter Optimization. *Applied soft computing*.

Hua Chen, Liang Wang, Shuang Li, and **Xiaohan Wei**. Operating Status Prediction Method for Gas Storage Compressors Based on BiLSTM. *Journal of Vibroengineering*.

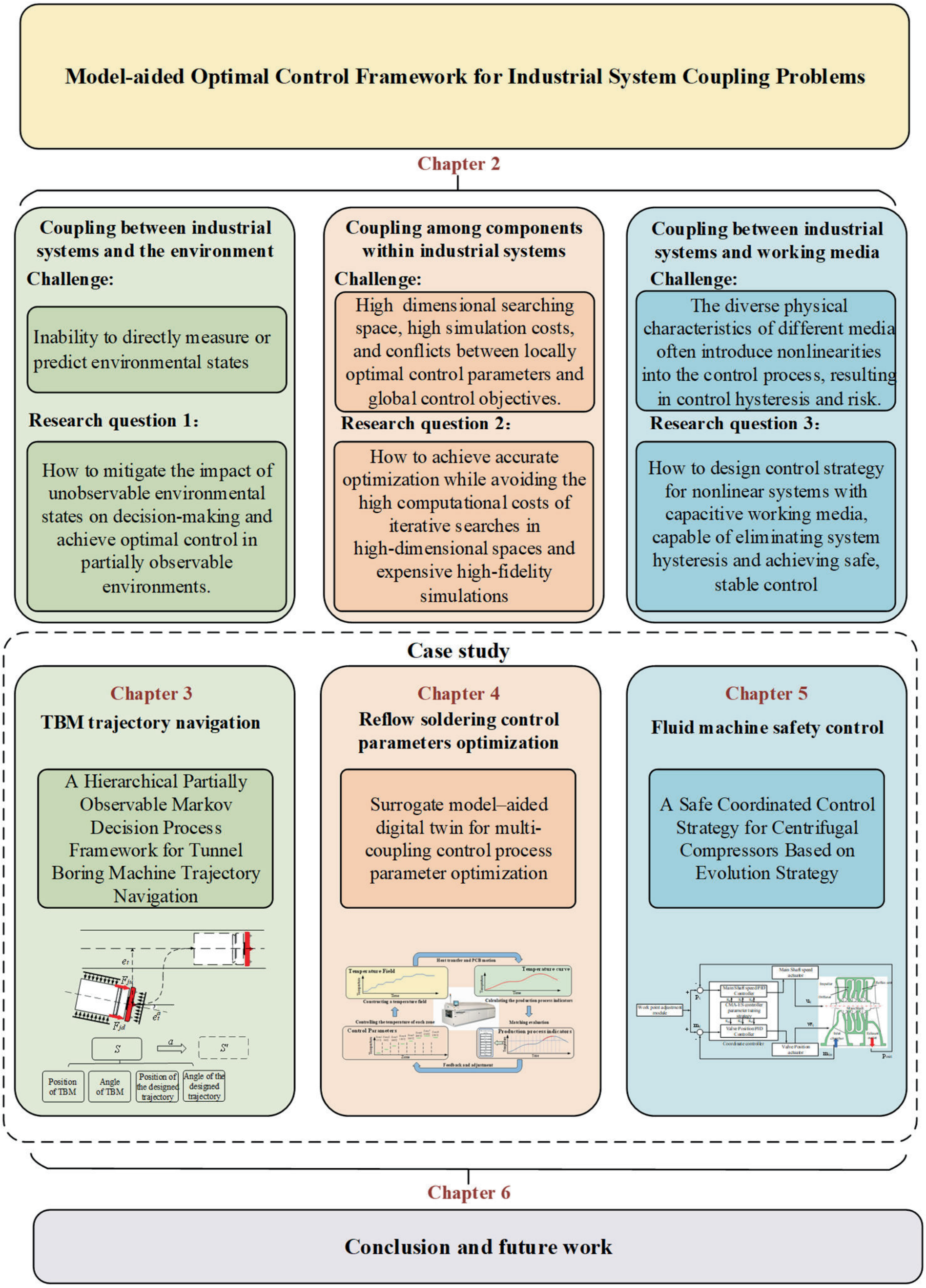

Figure 1.1: The structure of this thesis.