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Digital Twin Enabled Smart Control Engineering

– A Framework and Case Studies –

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Preface

This book presents the Digital Twin from a control engineering point of view, enabled by Smart Control Engineering, a new control paradigm that introduces smartness into classic control systems to produce smart feedback control systems for Industry 4.0 applications. A novel systematic developing framework is introduced for Digital Twin applications focused on control systems. It leverages the classic control engineering steps of Modeling, Analysis, and Design (M.A.D) with breaking technologies like multiphysics simulation, machine and deep learning, or data analytics to create Digital Twins that provide a realistic representation of the physical system to be controlled. Likewise, the concept of Smart Control Engineering is presented, focused on its integration with Digital Twins to introduce smartness intro control systems. Besides, a set of enabling capabilities resulting from Digital Twin integration are analyzed like fault detection, prognosis, life cycle analysis, and control performance assessment. Two case study examples of Digital Twin for process and motion controls are presented to demonstrate the applicability of the systematic design framework. The book has a support website where the readers can found the codes for the case study presented on the book which can be found at `https://www.theedgeai.com/dtandscebook`. The book is designed from the control engineering point of view but can be followed by the science and engineering community. It is organized as follows:

Chapter 1 presents the what is and what is not a Digital Twin, its requirements, structure, challenges, applications and state of the art regarding the current trends of Digital Twin in different fields like bioengineering, smart cities, transportation, logistics and controls.

Chapter 2 presents a systematic design framework for the Digital Twin for its application in control systems design. Likewise, a case study for the Digital Twin application for the design and control of a uniformity temperature control system is presented.

Chapter 3 is dedicated to the Enabling capabilities resulting from Digital Twin for control systems design like Control Performance assessment, Fault Detection Prognosis and Health Management. Also, a case study for Digital Twin enabling capabilities is presented for the fault detection and Remaining Useful Life estimation of the uniformity temperature control developed in chapter 2.

Chapter 4 introduces the concept of Smart Control Engineering as a new control paradigm based on smart systems combined with control theory enabled by Digital Twins and Self Optimizing Control as well as a Digital Twin based simulation benchmark for smart controllers assessment. In addition, two case studies are developed to analyze Smart Control Engineering: the uniformity temperature control developed in chapter 2 and 3 and a smart mechatronic system.

Finally, Chapter 5 discusses future research directions of Digital Twin, Smart Control Engineering, and the associated enabling capabilities like fault detection and Self Optimizing Control.

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Acronyms

ACP	Artificial, Computational, and parallel execution
AIC	Akaike Information Criteria
BIC	Bayesian Information Criteria
BJ	Box-Jenkins Model
CPA	Control Performance Assessment
CPC	Cognitive Process Control
CPS	Cyber-Physical Systems
DT	Digital Twin
FOPDT	First Order Plus Dead Time system
GCNM	Globalized Constraint Nelder Mead optimization
IA	Artificial Intelligence
IAE	Integral Absolute Error
IAI	Industrial Artificial Intelligence
ICT	Information and Communication Technologies
IID	Independent and Identically Distributed Random Variables
ISE	Integral Square Error
ITAE	Integral Time Absolute Error
IoT	Internet of Things
IIoT	Industrial Internet of Things
LTI	Linear Time Invariant System
MAD	Modeling, Analysis, and Design
MDL	Minimum Description Length
MIMO	Multiple Input Multiple Output System
MPC	Model Predictive Control
nAIC	Normalized Akaike Information Criteria
NM	Nelder Mead Optimization Algorithm
NRMS	Normalized Root Mean Square Value
PI	Proportional, Integral Controller
PID	Proportional, Integral, Derivative Controller
PWM	Pulse Width Modulation
RTO	Real-Time Optimization

RMS	Root Mean Square Value
RUL	Remaining Useful Life Estimation
SCE	Smart Control Engineering
SIMO	Single Input Multiple Output System
SISO	Single Input Single Output System
SOC	Self Optimizing Control
SPSA	Simultaneous Perturbation Stochastic Approximation
TIR	Thermal Infrared Camera

Chapter 1
Digital Twin Background

Abstract In the way towards Industry 4.0, the complexity of the industrial systems increases due to the presence of multiple agents, Cyber-Physical Systems , distributed sensing, and big data introducing unknown dynamics that affect the production goals of the manufacturing processes. Thus, Digital Twin is a breaking technology corresponding to the capacity of developing a virtual representation of any complex system in order to perform design, analysis, and behavior prediction tasks that enhance the understanding of these systems through new enabling capabilities like real-time analytics, parallel sensing, or Smart Control Engineering. This chapter presents the background of Digital Twin, the motivations of its use on smart control systems and an applications literature review on the recent years.

1.1 Introduction

The use of groundbreaking technologies in human history set milestones in the manufacturing processes, known as industrial revolutions. As shown in Fig. 1.1, during the 18th century, the first industrial revolution was powered by the steam powered machine, increasing the speed and quality of manufacturing processes. The second one occurred during the beginning of the 20th century by the introduction of the electric machine, reducing the factories power requirements, improving the manufacturing quality, and defining new concepts like the assembly line and pipeline production. The third industrial revolution carried out during the 1970s driven by computer-assisted manufacturing and robotic systems in the production lines defined the modern industry standards.

Since the 2000s, the fourth industrial revolution or Industry 4.0 is transforming the manufacturing processes into Cyber-Physical Systems (CPS) driven by Information and Communication Technologies . Its boundaries of the system are defined into physical and virtual spaces, with multiple individual agents interacting simultaneously to perform a complicated task. This integration pursues the generation of intelligent responses for each element based on the dynamic of the whole system