Jairo Viola and YangQuan Chen

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, enabling 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 (MAD) 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 into 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 chapters 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.

Merced, CA, USA *Jairo Viola*
March 2022 *YangQuan Chen*

Acknowledgements

The purpose of this monograph is to present Digital Twin (DT) and Smart Control Engineering (SCE) as drivers for introducing smartness in the classic closed-loop control. This book presents DT foundations, a systematic development framework for DT applications in control systems, the enabling capabilities derived from the introduction of Digital Twin and the concept of Smart Control Engineering powered by DT. This book is based on a series of our published papers and parts of the planned Ph.D. dissertation of the first author. While some of these materials were reused, we have rewritten most parts for this monograph.

In this journey through the novel field of Digital Twin and its applications in making control systems smart, we are grateful to many.

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Contents

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
MBD	Model-Based Design
MDL	Minimum Description Length
MIMO	Multiple Input Multiple Output System
MPC	Model Predictive Control
MWAS	Matlab Web App Server
nAIC	Normalized Akaike Information Criteria
NM	Nelder Mead Optimization Algorithm
NRMS	Normalized Root Mean Square Value
PCA	Principal Component Analysis
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
SDE	Stochastic Differential Equation
SIMO	Single Input Multiple Output System
SISO	Single Input Single Output System
SLDO	Simulink Design Optimization Toolbox
SOC	Self Optimizing Control
SPSA	Simultaneous Perturbation Stochastic Approximation
TIR	Thermal Infrared Camera