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Control and Scheduling Codesign

Flexible Resource Management in Real-Time Control Systems

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Preface

Recent evolutionary advances in information and communication technologies give rise to a new environment for Real-Time Control Systems. This is a new dynamic environment that features both resource limitation and workload variability. As a consequence, the availability of the computing and/or communication resources becomes typically uncertain in modern Real-Time Control Systems. In this context, the expected *Quality of Control* (QoC) of the systems cannot always be guaranteed by the traditional control systems design methodology that separates control from scheduling. From a resource scheduling perspective, the prevalent open-loop scheduling schemes in real-time systems obviously lack flexibility when applied to Real-Time Control Systems operating in dynamic environments. To make the best use of available resources, more holistic principles and methods need to be developed. These requirements motivate the recent technological trend towards the convergence of computing, communication and control.

This book is a monograph that covers our recent and original results in this direction. The main objectives of this work are:

(1) *To construct a unified framework of feedback scheduling that enables the integration of control with computing and communication.* This framework will encompass a set of concrete feedback scheduling methods and algorithms that are applicable to different systems. With these methods and algorithms, solutions are provided for some key issues in feedback scheduling, thus promoting the emergence of this area.

(2) *To enable flexible QoC management in dynamic environments with uncertainty in resource availability.* A number of new approaches to flexible management of the computing and/or communication resources in Real-Time Control Systems will be developed to maximize or improve the overall system performance.

With these objectives in mind, we focus on feedback scheduling strategies for flexible resource management in the context of real-time control. The traditional control systems design methodology and the simple control task model based on the fixed timing constraints are discarded. closed loop dynamic resource management schemes are built by means of control and scheduling codesign. The major tool used in this book is feedback scheduling. The introduction of feedback into dynamic resource management breaks the traditional open-loop mode of resource scheduling.

We are not interested in solutions that belong to any particular discipline, i.e. control theory, computer science or communication technology. Accordingly, we do not attempt to:

(1)*Design new control algorithms.* No innovation is made in this book regarding controller design that could make the control loops robust against delay, data loss or jitter. This is often difficult because it requires a solid foundation of mathematics. Furthermore, there has been extensive interest in this direction for many years, with an abundance of theoretical results produced.

(2)*Develop new real-time task scheduling policies.* Implementing a new scheduling policy demands support from the underlying platforms, e.g. the operating systems. Therefore, it is generally hard for a new scheduling policy to become practical even if it indeed performs better than existing ones in some situations. On the other hand, many mature scheduling policies are available in the area of real-time scheduling.

(3)*Develop new communication protocols.* Despite rapid evolution, none of the wireless technologies in existence was designed particularly for control applications. Intuitively, developing such a dedicated communication protocol (from scratch or based on some existing protocols) could better support wireless control. However, this is beyond the scope of this book due to its emphasis on networking.

While the framework presented is applicable to a broad variety of computing and communication resources, special attention of this book is paid to three representative classes of resources, i.e. CPU time, energy and network bandwidth. By exploiting the feedback scheduling methodology, we develop a set of resource management schemes. Numerous examples and case studies are given to illustrate the applicability of these schemes.

The inherent multidisciplinary property of the codesign framework makes the intended audience for this book quite broad. The first audience consists of researchers interested in the integration of computer science, communication technology and control theory. This book presents a unified framework as an enabling technology for codesign of computing, communication and control. Novel paradigms for Real-Time Control Systems research and development in the new technological environment also provide insight into new research directions in this emerging area.

The second audience is practitioners in control systems engineering as well as computer and communication engineering. Careful balance between theoretical foundation and real-world applicability makes the book a useful reference not only for academic research and study but also for engineering practice. Much effort has been devoted to make this book practical. For instance, the problems addressed are of remarkably practical importance; all solutions are developed with the practicability in mind.

This book is also of value to graduate students in related fields, for whom the tutorial introduction to feedback scheduling and the extensive references to the literature will be particularly interesting. The background of the reader assumed in the presentation encompasses a basic knowledge in feedback control theory, sampled-data control, and real-time systems. Prior experience with intelligent control, power-aware computing, and network bandwidth allocation is also helpful, though not necessary.

Outline of the Book

This book is broken into four parts, each part containing two chapters. The first part, Background, covers Chapters 1 and 2, in which the motivations, background information and basic framework for this work are given. Part II (CPU Scheduling) is concerned with scheduling the shared processor in multitasking embedded control systems. Chapters 3 and 4 belong to this part. Their focuses are on developing intelligent feedback scheduling methods by exploiting neural networks and fuzzy control respectively. While CPU scheduling is also involved, the main concern of Part III (Energy Management) that covers Chapters 5 and 6 is dynamic management of the energy consumption of embedded controllers. The general goal of this part is to reduce the CPU energy consumption while preserving QoC guarantees. The last part, Bandwidth Allocation, which covers Chapters 7 and 8, studies how to dynamically allocate available communication resources among multiple loops in networked control systems and wireless control systems respectively.

In Chapter 1 we give an overview of the field of control and scheduling codesign. The motivations for codesign of control and scheduling are illustrated. Recent trend towards the convergence of computing, communication and control is pointed out. After related work in the literature is reviewed, a perspective on feedback scheduling of Real-Time Control Systems is given. Chapter 2 presents a tutorial introduction to feedback scheduling. Background knowledge about sampled-data control and scheduling in real-time systems is outlined, which makes this book more self-contained. The temporal attributes of control loops are described. Motivating examples for applying feedback scheduling are presented. Key concepts, basic framework, and design considerations related to feedback scheduling are also described.

Chapter 3 concerns neural feedback scheduling. The primary goal is to overcome the disadvantages of overly large computational overhead associated with mathematical optimization routines. We present a fast feedback scheduling scheme to exploit feedforward neural networks. This scheme can dramatically reduce feedback scheduling overhead while delivering almost optimal overall control performance.

Chapter 4 presents a fuzzy feedback scheduling scheme based on fuzzy logic control. This scheme is independent of task execution times, robust to measurement noise, while handling uncertainty in resource availability in an intelligent fashion. Being easy to implement, the fuzzy feedback scheduler also incorporates quite a small runtime overhead.

Considering the unpredictability of task execution times as well as the variability of CPU workload, Chapter 5 develops a feedback control real-time scheduling methodology called Energy-Aware Feedback Scheduling. It integrates the management of both energy consumption and QoC. After analytically modelling the Dynamic Voltage Scaling system, a control-theoretic design and analysis method for feedback schedulers is proposed. Taking advantage of the basic framework of Energy-Aware Feedback Scheduling. Chapter 6 aims to achieve further energy consumption reduction while not jeopardizing the quality of control. For this purpose, we present an Enhanced Energy-Aware Feedback Scheduling scheme to exploit the methodology of graceful gradation.

Chapter 7 pays attention to multi-loop networked control systems. By exploiting codesign of control and network scheduling, we develop an integrated feedback scheduling scheme. This scheme can maximize resource utilization in the case of light workload and achieve graceful performance degradation under overload conditions. To attack the uncertainty in available communication resource in wireless control systems, Chapter 8 presents a cross-layer Adaptive Feedback Scheduling scheme that takes advantage of cross-layer design. It proves quite efficient to deal with channel capacity variations and noise interference. We also suggest an event-driven invocation mechanism for feedback schedulers to further improve the feedback scheduling performance.

We consider only linear time-invariant (LTI) systems in this book, though the proposed approaches are not only applicable to this class of systems. The control applications used as simulation examples are kept typical and illustrative to exhibit the wide applicability of the proposed approaches. For instance, the controlled processes studied include inverted pendulum, DC motor, and many others. The control algorithms cover PID (Proportional-Integral-Derivative), state feedback control with pole placement, LQG (Linear Quadratic Gaussian) controllers, etc. The control theory involved comprises classical control, modern control, as well as intelligent control. In addition, both of the two design methods for digital controllers i.e. discrete-time design and discretization of continuous-time controllers have been adopted in different simulations. Throughout the book, all simulations are conducted using Matlab/Simulink[1] along with the TrueTime[2] toolbox.

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1 Matlab and Simulink are registered trademarks of The MathWorks, Inc.

2 http://www.control.lth.se/truetime/

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We dedicate this book to our families.

Feng Xia
Youxian Sun

Notations and Symbols

AFS	Adaptive Feedback Scheduling
α	Voltage scaling factor, normalized CPU speed
$\alpha_{\min}$	Minimum allowable voltage scaling factor
BP	Back Propagation
c_i	Execution time of task i at actual CPU speed
$c_{i,\text{nom}}$	Execution time of task i at full CPU speed
$\hat{c}_i$	Estimated execution time of task i at actual CPU speed
$\hat{c}_{i,\text{nom}}$	Estimated execution time of task i at full CPU speed
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DVS	Dynamic Voltage Scaling
E	Normalized energy consumption of CPU
EAFS	Energy-Aware Feedback Scheduling
ECS	Embedded Control System
EDF	Earliest Deadline First
EEAFS	Enhanced Energy-Aware Feedback Scheduling
FFS	Fuzzy Feedback Scheduling
h_i	Sampling period of control loop i, period of task i
$h_{i,0}$	Nominal (initial) sampling period of task i
$h_{i,\max}$	Maximum allowable sampling period of control loop i
$h_{\min}$	Minimum allowable sampling period
IAE	Integral of Absolute Error
IFS	Integrated Feedback Scheduling
j	Invocation instant of a feedback scheduler
J_i	Control cost of control loop i
J_{SUM}	Total control cost of all control loops
k	Sampling instant of a control loop

K_D	Derivative coefficient of a PID controller
K_I	Integral coefficient of a PID controller
K_P	Proportional coefficient of a PID controller
MAC	Medium Access Control
N	Number of concurrent control loops/tasks
NCS	Networked Control System
NFS	Neural Feedback Scheduling
OFS	Optimal Feedback Scheduling
OLS	Open-Loop Scheduling
opDVS	optimal pure Dynamic Voltage Scaling
OSI	Open System Interconnection
PID	Proportional-Integral-Derivative
ρ	Deadline miss ratio
ρ_r	Setpoint for deadline miss ratio
QoC	Quality of Control
QoS	Quality of Service
r	Transmission rate of a network
r_i	Reference input of control loop i
RM	Rate Monotonic
RTCS	Real-Time Control System
SQP	Sequential Quadratic Programming
T_{FS}	Invocation interval of a feedback scheduler
U	CPU/Network utilization
U_{req}	Requested utilization
U_R	Utilization setpoint
w_i	Weighting coefficient of control loop i
WCET	Worst-Case Execution Time
WCS	Wireless Control System
WLAN	Wireless Local Area Network
y_i	System output of control loop i
η	Period scaling factor

Contents

PART I BACKGROUND

PART II CPU SCHEDULING

PART III ENERGY MANAGEMENT

PART Ⅳ BANDWIDTH ALLOCATION

PART I
BACKGROUND

Chapter 1

Overview

This chapter gives an overview of the field of control and scheduling codesign, thus constituting the background of this work. The features of modern real-time control systems are examined with respect to resource availability. The potential disadvantages of the traditional control systems design and implementation method when used in environments featuring resource limitation and workload variations are characterized. Thus the motivations for codesign of control and scheduling are illustrated. Recent trend towards the convergence of computing, communication and control is pointed out. With emphasis on feedback scheduling and real-time control, related work in the two research directions, integrated control and computing and integrated control and communication, is roughly reviewed respectively. A perspective on feedback scheduling of Real-Time Control Systems is also given.

1.1 Real-Time Control Systems

In recent years there are revolutionary changes in information and communication technologies [MUR03]. With the availability of ever more powerful and cheaper products, the roles that embedded computing and networked communication play in control systems engineering are becoming increasingly important. The number of networked embedded devices deployed in practice has been far more than that of various general-purpose computers including, e.g. desktop PCs [ARZ05a, BOU05, LOY03, XIA06b]. These devices are used in many application areas such as aerospace, instrument, process control, communication, military, consumer electronics, etc. In this context, networked embedded control systems have become unprecedentedly popular.

There is no doubt that control systems constitute an important subclass of real-time systems in which the value of the task depends not only on the correctness of the computation and/or communication but also on the time at which the results are available [LIU00, STA96]. Since almost all control systems in the real world are implemented upon specific computing and communication platforms using digital