Studies in Systems, Decision and Control

Volume 257

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Spandan Roy · Indra Narayan Kar

Adaptive-Robust Control with Limited Knowledge on Systems Dynamics

An Artificial Input Delay Approach and Beyond

Springer

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ISSN 2198-4182 ISSN 2198-4190 (electronic)
Studies in Systems, Decision and Control
ISBN 978-981-15-0639-0 ISBN 978-981-15-0640-6 (eBook)
https://doi.org/10.1007/978-981-15-0640-6

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Dedicated to my parents, sister and grandparents.
Spandan Roy

Dedicated to my former students.
Indra Narayan Kar

Preface

In the quest to negotiate the inevitable effects of parametric and non-parametric uncertainties in a system during a control task, researchers have broadly applied two different classes of control strategies, namely, adaptive control and robust control. However, while a conventional adaptive control requires structural knowledge of the system, a conventional robust control requires predefined bound on the uncertainties. It is often difficult to satisfy either of these constraints in practice. Under such circumstances, the recent research direction has reoriented toward developing adaptive-robust control (ARC) law that can address the issues while retaining the individual advantages of the adaptive and robust controllers. Unfortunately, to date, the state-of-the-art ARC designs have not been able to fully achieve the objective: they either depend on significant a priori knowledge of system model or impose restrictions on the state evolutions via various assumptions.

To reduce dependency on the accuracy of system modelling while designing a controller, researchers have also applied black-box techniques like neural-network (NN). However, such schemes require expertise knowledge apart from being computationally expensive. In such scenario, an alternate literature has grown where *time delay is invoked intentionally/artificially* into a delay-free system to approximate the unknown/unmodelled system dynamics. Such approximation method is typically called time-delayed estimation (TDE) or artificial delay-based approximation, and the resulting control law is termed in the literature as time-delayed control (TDC). Compared to an NN-based controller, TDC is found to be significantly easier to implement as well as it does not require any expertise knowledge.

In view of the capability of a TDE method in reducing dependency on system model, attempts have been made to reap this benefit to design ARC. Nonetheless, there exist unsolved design issues of TDC which, apart from restricting its flexibility in practical applications, even may cause serious impediment to system stability. Moreover, the state-of-the-art switching law based ARCs suffer from the *over- and under-estimation problems of switching gain*, where the first issue demands unnecessary high control input and the second one compromises tracking accuracy. These prevailing issues foster the aim of this book as *to develop an ARC framework for a class of uncertain systems with minimal knowledge of system dynamics model, which can alleviate the over- and under-estimation problems of switching gain*.

For control design purpose, this book particularly concentrates on a class of Euler-Lagrange (EL) systems which encompasses a large number of real-world systems ranging from simple robotic manipulator, mobile robot, pneumatic muscles to complex systems such as humanoids, ship dynamics, aircraft systems, etc. EL systems have found enormous applications over the years in multitude of domains such as industry automation, planetary mission, surveillance, etc., to name a few. Therefore, achieving autonomy in these systems while accomplishing a specified task has always attracted the control systems research community.

Based on the detailed discussions regarding the issues of conventional TDE-based controllers and of the ARCs in Chap. 1, this book brings out five major research outcomes spanning across Chaps. 2–6 and they are briefly enumerated below:

- A new stability analysis, based on the Lyapunov-Razumikhin theorem, is carried out in Chap. 2 to solve various design issues of the state-of-the-art TDE-based control designs. Accordingly, the study establishes a relation between controller gains and time delay; provides analytical measure to the impact of the selection of time delay on system stability and allows the continuous-time system to assimilate discrete-time feedback used for TDE process.
- A TDE-based ARC framework is proposed in Chap. 3 to solve the long standing challenge of alleviating the over- and under-estimation problems in the adaptive evaluation of switching gains.
- To reduce the effect of measurement error in the absence of state-derivatives, a new TDE-based controller as well as its ARC framework are derived in Chap. 4 via only position feedback. The proposed controllers utilize only past position data (for EL systems) to estimate the state-derivative terms.
- The Lyapunov-Krasovskii based stability notions for TDE-based designs, treated as alternate/parallel study to the Lyapunov-Razumikhin based analysis in Chaps. 2–4, are provided in Chap. 5.
- A new ARC strategy is derived in Chap. 6 which, in contrast to a TDE-based law, does not require *any knowledge of system dynamics terms*. Furthermore, the proposed ARC avoids any separate module for uncertainty approximation and hence, simplifies the controller structure.

To validate the effectiveness of all the controllers developed in this book, suitable experimental results are provided using a wheeled mobile robot which serves as an appropriate exemplar of EL systems.

This book is intended for graduate students who wish to work in the fields of artificial delay-based design TDC and ARC. Apart from being the first book on TDE that ensembles its motivation, origin, issues and corresponding novel solutions, this endeavour also extensively highlights how an ARC and a TDE method can benefit from each other when applied simultaneously.

Hyderabad, India
New Delhi, India
August 2019

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Acknowledgements

Research is not a singular journey, but an outcome of plurality. Besides the unconditional support of my family, I would like to acknowledge those who have helped me to grow as a researcher. I would like to thank my colleagues Drs. Sayan Basu Roy, Abhishek Dhar and Abhilash Patel for the various discussions leading to polishing and strengthening my existing knowledge base. I would like to express my gratitude to my Master's supervisor Prof. Shambhunath Nandy (CSIR-CMERI, India) and my Postdoc supervisor Prof. Simone Baldi (TU Delft, The Netherlands) whose dedication to work has been a great source of inspiration. For a Control Systems researcher, *negative feedback* is more important. With that spirit, I would like to thank those people whose (unjustified/unrealistic) comments/suggestions and attitude have taught me what *I should never become as a researcher*.

Hyderabad, India
August 2019

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Dr. Spandan Roy currently serves as an Assistant Professor at the Robotics Research Center, International Institute of Information Technology, Hyderabad (IIIT-H). He received his B.Tech. from West Bengal University of Technology, completed his M.Tech. in Mechatronics at the Academy of Scientific and Innovative Research, CSIR-Central Mechanical Engineering Research Institute, and received his Ph.D. at the Department of Electrical Engineering, Indian Institute of Technology, Delhi. He was a Postdoctoral Fellow at the Delft Center for Systems and Control, Delft University of Technology, The Netherlands. His main research interests are adaptive-robust control, artificial delay based design, switched systems and robotics.

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Acronyms

Abbreviations

ARC	Adaptive-Robust Control
ASRC	Adaptive Switching gain-based Robust Control
EL	Euler-Lagrange
LIP	Linear in parameters
LK	Lyapunov-Krasovskii
NLIP	Nonlinear in parameters
POTDC	Position Only Time-Delayed Control
ROC	Robust Outer-loop Control
SMC	Sliding Mode Control
TDC	Time-Delayed Control
TDE	Time-Delayed Estimation
UUB	Uniformly Ultimately Bounded
WMR	Wheeled Mobile Robots

Symbols

$\mathbb{R}$	Real Space
$\mathbb{R}^+$	Real line of positive numbers
$\mathbb{R}^n$	Real Space of dimension n
$\mathbb{R}^{n \times n}$	Real matrix of dimension $n \times n$
$\mathcal{C}$	Set of continuous functions
$\exists$	There exists
$\forall$	For all
$\vee$	Logical 'OR'
$\wedge$	Logical 'AND'
$\mathbf{I}$	Identity matrix with appropriate dimension

$\mathbf{\Xi} > \mathbf{0}(<\mathbf{0})$	Positive (negative) definite matrix
$\lambda_{\min}(\bullet)$	Minimum eigenvalue of the matrix $\bullet$
$\lambda_{\max}(\bullet)$	Maximum eigenvalue of the matrix $\bullet$
$\|\| \bullet \|\|$	Euclidean norm of the matrix $\bullet$
$(\bullet)_h$	The variable $(\bullet)$ is delayed by an amount h as $(\bullet)(t-h)$ where $h > 0$