Performance of Nonlinear Approximate Adaptive Controllers

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To Beata and Nic

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Preface

In recent years there has been wide interest in nonlinear adaptive control using function approximator models, for either tracking or regulation, often described as 'neural network based control'. This is evidenced by the wide publication of such research in journals and many sessions in recent international conferences.

This field contrasts to the traditional domain of adaptive control, where the model is typically thought to contain uncertain 'physical' parameters. In function approximator designs systems are considered which contain uncertain nonlinear functions which are approximated using function approximator models. Many control researchers have cast doubt on the practicality of such approximate model based designs, and have further questioned whether there is any novelty in such an approach: surely such controls are just robust adaptive designs, and hence there is nothing new to be said? A few years ago we approached this subject from a similar critical viewpoint, but have become convinced that there are indeed many interesting features about the approximate adaptive approach that do not appear in the classical parametric theory. The purpose of this book is intended to describe this viewpoint. We will describe the approximate model philosophy and its setting, and *rigorously compare the performance of such controls against competing designs*. This comparison will thus highlight the situations in which the approximate model based designs are the most appropriate and conversely will indicate the scenarios in which other designs are more appropriate. Thus this book not only presents a description of a topical aspect of contemporary research and control practice, but also places the algorithms proposed in a wider comparative setting.

It is apparent that utilising an approximate model in an adaptive control design, and then using a robust modification to the adaptive laws to ensure stability in the face of approximation errors, yields a control design which is essentially just a semi-global robust adaptive design. However, this line of reasoning may obscure the implicit (and critical) choice that has necessarily been made: namely the choice of model. Different choices of models (even with identical approximation abilities) yield controllers with very different output and control transient performances. Examining this issue is one of the main themes of this book: the control designs are modifications to (now standard) Lyapunov designs for, e.g., matched, strict feedback and output feedback systems and the theme is to examine the performance of these designs for different choices of approximation theoretic models.

To develop a firm basis on which to judge the designs it is necessary to develop uncertainty models. As the designs are oriented towards systems with non-parametric, nonlinear, static uncertainties, these uncertainty models form subsets of function spaces, and are characterised here by spatial (weighted) L^2 norm bounds, spatial (weighted) L^∞ norm bounds and approximation theoretic smoothness constraints.

It is necessary to evaluate transient performance in a realistic but tractable manner. Throughout the book we primarily focus on LQ performance. This is modified in a variety of ways to suit the particular problem being considered (e.g. exponentially weighted or truncated for the tracking designs). The critical point is that all these costs penalise both the state/output transient *and the control effort*. Until the control effort is incorporated into the cost, many nonlinear designs can achieve an arbitrarily good output performance with respect to many singular cost functionals by tuning gains appropriately. Yet these gains lead to high control effort. Therefore, and for the first time in the nonlinear adaptive literature, we take this trade-off fully into account when evaluating designs. *The handling of the penalty on the control effort is the single most important contribution of this research*, and indeed the questions raised about controller comparison cannot be meaningfully answered in its absence.

Within this uncertainty/performance framework we demonstrate by a rigorously constructed example that a bad choice of function approximator model can cause an inevitable performance degradation, even when all free parameters of the system (adaption gains, etc.) are tuned optimally. For example, it is shown that the performance of spline based adaptive controllers necessarily diverges when a uniform knot lattice is refined: this is in spite of the fact that finite performance can be achieved for any particular refinement if the gains are tuned appropriately. We also demonstrate that this scaling problem can be avoided if the model is chosen more appropriately, and constructions for such models and associated gains are given. These constructions essentially exploit multi-resolution properties of the models; this structure is absent in the spline example. These two complementary results then form the basis for the development of any approximate adaptive results: subsequently it is necessary to demonstrate both stability/asymptotic performance and also good scaling properties.

Finally we address the complexity issue. The rival algorithms (i.e. those which can operate on the same problem domains, e.g. robust backstepping, or adaptive stabilisation designs based on estimating the uncertainty level rather than physical parameters) are considerably simpler to implement. Thus the last theme of this book is to compare the approximate model-based designs against their competitors. In particular we show situations in which the approximate designs can be expected to out-perform other designs, and thus justify their complexity. Conversely we also show situations in which the rival algorithms are the better choice.

Besides the aim of critically evaluating a particular class of control designs, the second purpose of the book is to showcase a particular approach and the associated toolkit, which permits a quantitative comparison to be made between competing control designs. This toolkit is developed as required throughout the book, but on its own provides a constructive framework for estimating both upper and lower bounds of a variety of performance cost functionals for Lyapunov based control designs. We therefore believe that this book has a widespread appeal, of interest far beyond just those who are interested in the particular class of designs we consider in detail.

We intend that this book should appeal to a wide audience. We hope that it will be read by both control engineers, mathematicians with interests in control theory and computer scientists with interests in machine learning. The basic pre-requisite is a certain level of mathematical maturity, in particular an understanding of basic analysis and functional analysis. The book [24] provides the required material at about the right level. We do not explicitly assume any knowledge of control theory, but a basic appreciation of the techniques and goals of the subject would undoubtedly be useful. A good introduction to control theory at an appropriate level of mathematical sophistication can be found in [48].

As with all researchers, we owe a great debt of gratitude to a number of people. In particular, our colleagues and students, both past and present, in Southampton, Budapest and elsewhere, have been a constant source of inspiration. The figures were drawn with the help of John Norton and the simulations were completed by a project student who wishes to remain anonymous. Kathryn Sharple at Wiley deserves a strong vote of thanks for supporting us, and for believing that the ever-receding delivery deadline would one-day be met! Most importantly our families have continued to earn our gratitude for their forebearance of this lengthy project.

Southampton and Budapest.
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