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KTH Electrical Engineering

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Report on the Doctoral Thesis "Active Adaptive Control" by Jan Rathouský

The theory for optimal control under model uncertainty was developed around the 1970's under the 'label' dual control. The problem is highly relevant in practical applications for the following reason. Process models are never exact and even if a model is sufficiently accurate after the commissioning of a control system, processes tend to change over time due to, e.g. wear and tear or changes in feed composition, degrading the quality of the model and hence degrading control performance. Unfortunately, data collected under routine operation of a plant tend to contain little information of use for improving a model's quality. The reason being that the very purpose of control is to reduce process variations. However, unlike classical feedback control, dual control takes the model error into account in the control problem and excites the process so that data becomes informative with respect to improving the model. Such 'perturbations' typically worsens control performance but in dual control the conflicting objectives of control versus modeling are balanced in an optimal way.

The number of potential applications of dual control is unlimited. Unfortunately, it is virtually impossible to implement this type of optimal control as the computational complexity "explodes" with the length of the time interval over which the problem is to be solved. Therefore, a range of methods approximating dual control have been proposed during the last four decades.

Cautious control is one such method which has as key characteristic that the model uncertainty is incorporated in the control objective. However, this type of control does not take into account that it can improve the model quality. Rathouský revisits this method and in Chapter 2 *provides a novel and elegant derivation of the method for the case of an ARMAX model* - a model class that frequently is used since it can model disturbances. By assuming the MA-part of the noise model to be known, he firstly shows that state and model parameters can be estimated by a standard Kalman filter if a specific state-space realization of the model is used. Furthermore, *by another clever choice of state-space realization he can derive the cautious controller in a very compact way.* He then proceeds in Chapter 3 by analyzing the asymptotic behavior of this controller, i.e. what happens as time grows unbounded. It turns out that this controller is governed by a recursive matrix equation that has strong similarities with the so called Riccati equation, which in turn governs optimal control when there is no model uncertainty. This Riccati like equation was analyzed by Athans et. al. in the 1970s for scalar, and higher order systems with a particular structure of the uncertainty. For the case when the model is stabilizable and observable, if and only if conditions for when there there exists a fix point to the Riccati like equation, and it is also shown that then the recursive equation will converge to this matrix. The case when there is no fix point is also studied and it is shown that suitably normalized, the recursions converge. He also shows that regardless of if the Riccati like recursions converge or not, the corresponding control law converges.

In summary, Rathouský provides a very general analysis of dual control of ARMAX models where the A and B parts are uncertain.

Another approximation of dual control is active control where a model quality measure is incorporated in the control law. This can be done either as a constraint or as in this thesis as the objective function complemented with a constraint on the performance degradation of the control performance. In Chapter 4 a single step active control strategy is considered, where it is

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assumed that the model uncertainty can be influenced by the control actions in the first step after the current time, while remaining actions leave it unaffected. The approach is studied in a simple simulation setting. For ARX-models, the concept is further developed in Chapter 5 into a multi step method. The idea is to maximize the smallest eigenvalue of the information matrix over the control horizon with a constraint on the performance degradation from the nominal control performance. The resulting algorithm is non-convex and four different relaxations are considered. The first bounds eigenvalues uses Gershgorin circles, the second tries to enforce orthogonal regressors, and the third, and most sophisticated one, uses a finite sample overbound on the smallest eigenvalue. The third algorithm is thoroughly analysed in Chapter 6 where stability and convergence are established. The main issue with this ellipsoidal algorithm is the computational complexity and the fourth relaxation this issue is addressed using an ellipsoidal outer-bounding technique.

In summary regards to active control, while there have been several contributions related to the work in this thesis over the past 7-8 years, *Rathouský makes several important contributions to the area: Firstly, while most contributions have looked one step ahead, the formulation in Chapter 5 opens up for a longer horizon allowing for greatly improved performance. Secondly, the formulation of the problem as the maximization of some quantity of the information matrix subject to a constraint on the control performance is new and very interesting.* Indeed there is a parallel development in my own lab but the idea was first published by Rathouský and co-workers in 2013, and furthermore this just reinforces the notion that this is a timely contribution. *Finally, several new methods to solve the resulting non-convex optimization problem are proposed.*

Topics for discussion at the thesis defence

- Chapters 3-4 contain a very nice analysis of the algorithms governing cautious control. But little is said regarding the impact these results may have for optimal control under uncertainty and their interpretation. So what have we learnt from this analysis?
- In Note 3.3 on p 42, the author refers to the matrix H_N. Where is it defined?
- In Theorem 3.21 on p 53 there are no requirements on observability or stabilizability. Is this type of assumptions not required here? And if not, why not? And what about semi-definiteness of G_0?
- In Chapters 5-6 you propose some relaxations (Gershgorin, orthogonal regressors, ellipsoidal algorithm) to problem (5.28) but very little is mentioned regarding the properties of these relaxations. Can something be said about the properties? Convexity? Numerical experience? Which one is to be preferred?
- Is the a_{ij} on top of p 79 defined correctly?
- Bottom of p. 85. What is m_k(U)? And next page v_U?
- The active adaptive approach taken in Chapters 5-6 can be seen as a computational relaxation of dual control. It would be interesting to hear the candidates thoughts on the possibility to get even closer to dual control, still maintaining a computationally feasible algorithm.

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Summary

Overall the candidate has made a number of pertinent contributions to an area that could be characterized as approximate optimal control under uncertainty. The area has a long history and is technically very challenging so it is non-trivial to make contributions. It is also an area which has high practical relevance and which still is very active. Considering this, the candidate has made several important formal contributions to the area, most notably for cautious control. He has also made important contributions conceptually to the area. Most notably in terms of a practically relevant and implementable formulation of active control. The objectives of the work have clearly been met and the candidate has demonstrated ample creativity and that he has mastered the technical machinery involved. I believe that his work will have a strong impact on future work in the area.

The author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving the Degree of Ph.D.

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