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RECENT ADVANCES IN ROBUST ADAPTIVE CONTROL

by

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EXTENDED ABSTRACT

In this talk we discuss a general philosophy for designing "robust" adaptive multivariable feedback control systems for plants that include both unmodeled dynamics and uncertain real parameters in the plant state description. The adjective "adaptive" refers to the fact that the real parameter uncertainty and performance requirements require the implementation of a feedback architecture with greater complexity than that of the best possible non-adaptive controller. The word "robust" refers to the desire that the adaptive control system remains stable and meets the posed performance specifications for all possible "legal" parameter values and unmodeled dynamics.

Early approaches to adaptive control, such as the model-reference adaptive method (MRAC) and its variants, were concerned with real-time parameter identification and simultaneous adjustment of the loop-gain. In the model-reference method the emphasis was on proving convergence to the real parameter and subsequent deterministic Lyapunov arguments for closed-loop stability. However, the assumptions required for stability and convergence did not include the presence of unmodeled dynamics, immeasurable disturbances and sensor noise. Moreover, no explicit performance requirement was posed for the adaptive system; rather the "goodness" of the model-reference design was by the nature of the command-following error based upon simulations. Classical model-reference adaptive systems would indeed become unstable in the presence of disturbances and high-frequency unmodeled dynamics.

More recent approaches to the adaptive problem involved multiple-model techniques. The (large) parameter uncertainty set is subdivided into smaller subsets, each giving rise to a different plant model but with reduced parameter uncertainty. One then designs a set of control gains or a dynamic compensator for each model so that if indeed the true parameter belongs to a specific model a "satisfactory" performance was obtained. The identification of the most likely model is carried out by a "supervisor" which either switched in and out one of several controllers based primarily on deterministic concepts or relied upon stochastic identification concepts that generate on-line posterior probabilities reflecting which of the models is more likely. In the latter approach the controllers could be designed either by classical LQG methods or by using more sophisticated methods.

In all adaptive methods that employ multiple models, the complexity of the feedback

system will depend on the number of models employed. By decreasing the size of the parametric subsets one would obtain more models. Thus, all multiple model approaches must address the following:

(a) how to divide the initial large parameter uncertain set into N smaller subsets,
(b) what should be the size of each subset, and
(c) how large should N be?

Up to the present time the approaches available in the literature use either the Vinnicombe metric to measure the "distance" between different linear systems or (in the stochastic versions) the Baram probabilistic metric. The emphasis was focused upon feedback stability and little attention was paid to any robustness requirements on guaranteed adaptive performance.

In this talk we shall focused on explicitly defined "robust performance" requirements on the adaptive system implemented by the RMMAC.

If we turn our attention to the non-adaptive literature there exists a well-documented design methodology, and MATLAB design software, for linear time-invariant plants that addresses simultaneously both robust-stability and robust-performance in the presence of unmodeled dynamics and parametric uncertainty as well as exogenous disturbances and sensor noise. This methodology, pioneered by Doyle et al, is often called the mixed-m design method. The mixed-m design method incorporates the state-of-the-art in non-adaptive multivariable robust control synthesis and exploits the proper use of frequency-domain weights to define desired performance. Typically, using the mixed-m design method, one finds that as the size of the parametric uncertainty is reduced the guaranteed desired performance, say disturbance-rejection, increases. Unfortunately, very little has been done in integrating the non-adaptive mixed-mu design methodology with that of robust adaptive control studies; even though it should be apparent that the mixed-m design method should provide us guidance on the selection and number, N, of the models to be used in any multiple-model adaptive control scheme.

We now summarize how in the RMMAC method we integrate the mixed-m synthesis with multiple model adaptive control. We concentrate on improving the performance by maximizing the disturbance-rejection capability in the presence of noisy sensor measurements, unmodeled dynamics and parametric uncertainty. Moreover, we use explicit performance requirements for the design of the

Step 1. We use the mixed-m synthesis method to design the best non-adaptive controller for the original large parameter uncertainty set. We increase the "gain" of the output performance weight until the mixed-m upper bound reaches unity. This defines the "best" non-adaptive controller.

Step 2. We calculate an upper bound for possible performance by neglecting parametric uncertainty, but including unmodeled dynamics, for the same type of performance specification. We construct this upper bound on performance by designing robust controllers using the complex-m method and varying the real parameter over the uncertainty set. In essence this could lead to an adaptive multiple-model design where the number of models, N, is infinite.

Step 3. Since now we have both an upper bound and a lower bound on performance, we can make an intelligent choice on how to specify the desired performance requirements for the multiple-model adaptive system. We shall describe in the talk the specific way this is done using specific numerical examples; the idea is to guarantee an adaptive performance of, say, at least 80% of the unattainable upper performance bound by using the smallest possible number of models, i.e. uncertainty subsets.

This design methodology of Step 3 also defines the specific size of each uncertainty subset and it naturally includes any limits on disturbance-rejection that may arise from non-minimum phase zeros, unstable poles, and unmodeled dynamics. As the performance requirements become more stringent, for example by increasing the bandwidth of the output frequency weight, the minimum number of required models increases. In this manner, we fully quantify how the computational complexity of the adaptive system (as a function of the number N of required models) changes as we make our performance requirement more stringent.

The procedure summarized above can be used with any of the adaptive multiple-model methods. We shall illustrate its detailed design and properties, using extensive Monte Carlo simulations, by using the RMMAC method in the context of dynamic hypothesis-testing, which involves generating the posterior probability for each model. The important point to remember is that all multiple-model adaptive schemes require the definition of the minimum number of models required to achieve both robust stability and robust performance, and these can only be defined after we pose realistic performance requirements for the adaptive system as summarized in Steps 1 to 3 above.

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Michael Athans was born in Drama, Greece on May 3, 1937. He attended the University of California at Berkeley from 1955 to 1961 where he received his BSEE in 1958 (with highest honors), MSEE in 1959 and Ph.D. in control in 1961. From 1961 to 1964 he was employed as a member of the technical staff at the MIT Lincoln Laboratory, Lexington, Mass. where he conducted research in optimal control and estimation theory. From 1964, until his early retirement in 1998, he was a faculty member in the MIT Electrical Engineering and Computer Sciences department, where he held the rank of Professor. He also was the director of the MIT Laboratory for Information and Decision Systems (LIDS) from 1974 to 1981. He acted as the thesis supervisor for 41 MIT doctoral students and over 80 Master's students. In 1978 he co-founded ALPHATECH Inc., Burlington, Mass., where he served as Chairman of the Board of Directors. He has also consulted for numerous other industrial organizations and government panels. In 1995 he was Visiting Professor in the Department of Electrical and Computer Engineering at the National Technical University of Athens, Greece. In 1997 and since 1998 he is a Visiting Research Professor in the Institute for Systems and Robotics, Instituto Superior Técnico, Lisbon, Portugal.

Dr. Athans is the co-author of *Optimal Control* (McGraw Hill, 1966), *Systems, Networks and Computation: Basic Concepts* (McGraw Hill, 1972) and *Systems, Networks and Computation: Multivariable Methods* (McGraw Hill, 1974). In 1974 he developed 65 color TV lectures and study guides on *Modern Control Theory*. In addition he has authored or co-authored over 350 technical papers and reports. His research interests and contributions span the areas of optimum system and estimation theory, robust and adaptive multivariable control systems, and the application of these methodologies to defense, large space structures, IVHS transportation systems, aerospace, marine, automotive, power, manufacturing, economic, and military C3 systems. His latest research interests focus on dynamic models of the human immune system and robust adaptive control methodologies.

In 1964 he was the first recipient of the American Automatic Control Council's *Donald P. Eckman Award* "for outstanding contributions to the field of automatic control". In 1969 he was the first recipient of the *Frederick E. Terman Award* of the American Society for Engineering Education as "the outstanding young electrical engineering educator." In 1980 he received the second *Education Award* of the American Control Council for his "outstanding contributions and distinguished leadership in automatic control education." In 1973 he was elected Fellow of the IEEE and in 1977 Fellow of the AAAS. In 1983 he was elected Distinguished Member of the IEEE Control Systems Society. He received the *1993 H.W. Bode Prize* from the IEEE Control Systems Society, which also included the delivery of the prestigious *Bode Plenary Lecture* at the 1993 IEEE Conference on Decision and Control. He was the recipient of the *Richard E. Bellman Control Heritage Award* of the American Automatic Control Council "In Recognition of a Distinguished Career in Automatic Control; As a Leader and Champion of Innovative Research; As a Contributor to Fundamental Knowledge in Optimal, Adaptive, Robust, Decentralized and Distributed Control; and as a Mentor to his Students" presented in June 1995 at the American Control Conference. In 1996 he was awarded honorary doctorates from the National Technical University of Athens, Greece, and from the Technical University of Crete, Chania, Crete, Greece. In July 2002 he was awarded the *Ktisivos Award*, “In recognition of contributions to control and estimation theory, awarded by the Mediterranean Control and Automation Association. He was the recipient of a *Polish Academy of Sciences Medal*, “For contributions to Control Theory” in Warsaw, Poland, on June 30, 2005. In 2006 the Institute of Electrical and Electronic

Engineers (IEEE) elected him Life Fellow.

Professor Athans has served in numerous committees of IEEE, IFAC, AACC and AAAS; he was president of the IEEE Control Systems Society from 1972 to 1974. In addition he is a member of AIAA, Phi Beta Kappa, Eta Kappa Nu, and Sigma Xi. He has served as Associate Editor of the IEEE Trans. on Automatic Control, Journal of Dynamic Systems and Control, and the IFAC journal "Automatica."