September 2006

Simple Adaptive Control - The Stable Direct MRAC

Itzhak Barkana
Kulicke & Soffa Industries, Inc.,
Fort Washington, PA, U.S.A.

Description of the Workshop

This course intend to show that stable adaptive controllers can be easily implemented in large real-world applications, such as UAVs, re-entry vehicles, flexible structures, missiles, etc. The course will try to explain why in spite of successful proofs of stability and even successful demonstrations of performance, the use of Model Reference Adaptive Control (MRAC) methodologies in practical real-world systems was met with strong reluctance by practitioners and has remained very limited. The practitioners seem to have a hard time figuring out the passivity (or Strictly Positive Realness) conditions that can guarantee stable operations of adaptive control systems under realistic operational environments. Besides, it is difficult to measure the robustness of adaptive control system stability and allow it to be compared with the common and widely use measure of phase margin and gain margin that is utilized by present, mainly LTI, controllers. Furthermore, it seems to be commonly agreed that the adaptive control gains do not converge even in most ideal perfect following situations, and recent counterexamples apparently show that adaptive systems may totally diverge even when all required conditions are fulfilled.

The workshop starts with a brief review of various adaptive control strategies and in particular revisits the fundamental qualities of the customary direct MRAC methodology, its basic idea and its important contribution to stability analysis based on Lyapunov techniques. It also describes some of its basic drawbacks that seem to originate in particular in the role that the so-called Model Reference must play for the stability of the adaptive systems, and therefore must basically be of the same order as the plant. This fact inherently carries within it the various problems that appear under the customary names of "unmodeled dynamics" and the permanent need for "sufficient excitation."

The course then explains how those drawbacks have been addressed and eliminated within the frame of the so-called Simple Adaptive Control (SAC) methodology. SAC has been conceived because of the need for adaptive control methods in very large systems such as large flexible structures, etc., where the use of models of the same order as the plant was naturally excluded. This approach required adding another element that would take care of stability and therefore the role was the model was reduced to only be the generator of the desired trajectory. The workshop will show that, while initially SAC was considered even by its own developers to be just a modest version of the standard MRAC that should only be used because of its simplicity of implementation, the workshop shows that it was only because mathematical tools of analysis that could reveal its real potential were missing.

To this end, it will be shown that the sufficient passivity conditions that can guarantee stability with adaptive controllers have been significantly mitigated and can be clearly stated in such terms as minimum-phase and positive CB product and lead to similarly clear proofs of stability that leave no room for open questions or counterexamples. Besides, the Parallel Feedforward Configuration allows using basic stabilizability properties to augment the plant in such a way that the passivity conditions are satisfied, even when the original plant is both non-minimum-phase and unstable. New mathematical tools for stability analysis are presented and it is shown that they allow proving the convergence of the adaptive control gains, an issue that has remained open for more than 30 years. The previous counterexamples to MRAC will be revisited as they become just simple, successful, and stable applications of SAC. Realistic examples of flight control and others will also be used to illustrate the stability robustness and the performance of Adaptive Control systems based on SAC and that show that ultimately SAC is the Stable Direct MRAC methodology.

Course outline

1) Short review of classical Model Reference Adaptive Control (MRAC):
   - basic ideas
   - contributions to stability analysis
   - inherent drawbacks: passivity conditions, "unmodeled dynamics" and the need for "sufficient excitation"
2) New, mitigated, passivity and "almost passivity" conditions can be used to prove stability with adaptive controllers.
3) Review of counterexamples that diverge under MRAC, although they seem to satisfy all conditions required for stability and therefore seem to demonstrate that previous assumptions may not be sufficient to guarantee stability with MRAC.
4) The Simple Adaptive Control (SAC) methodology which was developed as a simplified and modest alternative to MRAC, yet ultimately seems to eliminate the drawbacks related to MRAC.
5) The Modified Invariance Principle and its use for the proof of stability and asymptotically perfect tracking for SAC. It is shown that the new, mitigated, "almost passivity" conditions are indeed sufficient to guarantee robust stability with SAC and ultimate convergence of the adaptive control gains.
6) Review of MRAC "counterexamples" shows that they are just simple, stable and well-behaving examples under SAC.
7) Because the control community at large seems to avoid using adaptive controllers and instead is trying to use "safe" gain scheduling techniques, an example illustrates the danger involved with the belief that LTI system theory and its safety gain and phase margin can be used in real-world changing environments.
8) Parallel Feedforward Configuration (PFC): basic stabilizability properties of plants, usually available for design, can be used so SAC can be applied with systems that do not inherently satisfy the basic "almost passivity" conditions.
9) Robustness with noise: a simple σ-term can be used to add the necessary robustness so SAC can be applied in those situations where perfect tracking is not possible, so that a robustly stable adaptive Control system can be implemented and used in the real world realistic environments.

Lecturer: Itzhak Barkana

<u>RESUME</u>

Itzhak Barkana has received his PhD degree in 1983 from Rensselaer Polytechnic Institute (RPI). He is a Fellow with Kulicke and Soffa Industries, Inc., Fort Washington, PA, USA. In this job he is an Internal Technical Consultant and authority for all problems related to systems and controls of fine machines motion control, design of optimal trajectories of motion, system analysis for both power consumption and performance. Since 1988 has also been an Adjunct Professor with Drexel University in Philadelphia. Has developed self-tuning algorithms and specialized feedback and feedforward control techniques that had pushed forward and permanently maintained the K&S bonding machines as the fastest and the most precise in the world. Has analyzed and solved the problem of "machine singing," i.e. persistent oscillations that occur in spite of the fact that the gain and phase margin seem more that sufficient. Has been a leading developer of the Simple Adaptive Control (SAC) methodology and has developed the fine theoretical points needed to guarantee robust stability of the adaptive control systems. Has continued to develop the theory related to implications of adaptive control techniques, including a Modified version of the LaSalle's Invariance Principle with valuable implications for the guarantee of stability of adaptive controllers in practical applications. Has defined and clarified the underlying theoretical "almost strictly positive real" conditions needed for stable adaptation. Recently, has solved the question of ultimate adaptive gains values that had remained open for more than 30 years. Most recently has also eliminated the need for symmetry from positive realness condition in multivariable systems that has apparently limited the applicability of adaptive techniques for more than 40 years.

In 2002 has received the Benjamin Franklin Key Award from Philadelphia Chapter of IEEE for "advancing the theory and practice of adaptive control, and in so doing, making major contributions to improving the speed and accuracy of specialty robotics for the semiconductor industry." These techniques helped to extend the life of wire bonding technology. As a result of this work, the challenge of portability – the ability to repeatably perform the same task on different machines – was solved. The time duration of bond table motion was reduced by more than 60%, dramatically increasing productivity, and the accuracy limit was lowered from more that 100 microns in the late 1990s to 35 microns in the current generation of Maxμm bonders. The robustness of the algorithms has been proven over the last 12 years by its successful implementation in tens of thousands of machines representing various platforms. It is one of the major innovations that have made K&S wire bonders the world industry leaders.
Is co-author of the book: "Direct Adaptive Control Algorithms – Theory and Applications" and has published 3 chapters in books and more than 80 papers in Journals and technical Conferences.