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STATUS REPORT #2
ON
NONLINEAR AND ADAPTIVE CONTROL

NASA GRANT NSG 2-297

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0. SUMMARY

This status report overviews the research on Nonlinear and Adaptive Control carried out at the MIT Laboratory for Information and Decision Systems under NASA grant NAG 2-297 for the time period 1 May 1985 to 31 December 1985. Participating faculty were Professors Gunter Stein, Lena Valavani, and Michael Athans (principal investigator). The grant monitors are Dr. George Meyer (NASA Ames Research Center) and Mr. Jarrell R. Elliott (NASA Langley Research Center).

The primary thrust of the research is to conduct fundamental research in the theories and methodologies for designing multivariable feedback control systems; and to conduct feasibility studies in application areas of interest to our NASA sponsors that point out advantages and shortcomings of available control system design methodologies.

The theoretical research overviewed in this status report is focused on adaptive and nonlinear systems. On-going feasibility studies relate to the multivariable control of forward-swept wing aircraft, and twin-lift helicopter systems.

1. PROGRESS ON ADAPTIVE CONTROL THEORY

A major phase of our proposed research has reached a significant milestone with the completion of the Ph.D. thesis by D. Orlicki ," Model Reference Adaptive Control Systems Using a Dead-Zone Nonlinearity " in April 1985. The thesis was co-supervised by Profs. Valavani and Athans, with Prof. Stein being a reader.

In this research we were able to develop new algorithms, of the MRAC type, which have guaranteed local stability properties in the presence of unmodeled dynamics and unmeasurable disturbances. To prevent the instability of the classical MRAC schemes, we have used the concept of intermittent adaptation; loosely speaking, this concept prevents the updating of uncertain plant parameters whenever the identification information is of dubious quality due to the simultaneous presence of unmodeled dynamics and disturbances which cannot be measured. Thus, we only adapt whenever we are sure that the real- time signals contain relevant information.

It is a highly nontrivial manner to decide, in real-time, when to adapt and when to (temporarily) stop the adaptation. Our new algorithms involve the real-time monitoring of easily measurable signals, and require the capability of computing discrete Fast Fourier transforms (DFFT) for those signals

Intermittent adaptation is implemented by blending the real-time spectral information generated by the DFFT's with variants of the model reference algorithms. The algorithms can be implemented through the use of a dead-zone nonlinearity whose width changes in real time based upon the DFFT calculations. To the best of our knowledge, this is the first time that an adaptive control algorithm has been developed that requires extensive spectral calculations so as to guarantee stability-robustness.

Although our intermittent adaptation algorithms represent a true advance in the state of the art, and undoubtedly will become controversial because of their increased computational requirements, nonetheless the most important by-product of our research during the past year is a detailed appreciation of the immense complexity of the adaptive control problem. In point of fact, we are convinced that new and different approaches to the robust adaptive control problem must be developed. There are simply too many hard questions, only tangentially related to adaptive control, that must be posed first, and of course answered, before we can proceed with confidence to using adaptive control to regulate physical systems, and especially multivariable ones. We briefly outline these key questions that we have been investigating in the sequel.

Adaptive Identification of Model Errors. Classical adaptive control algorithms use a postulated dynamic system order, i.e. a transfer function with fixed numbers of poles and zeros, and then use (explicit or implicit) identification to improve the prior estimate of the model uncertain parameters. In robust adaptive control this is necessary, but by no means sufficient. What is required is the development of a new class of adaptive identification algorithms which, with a finite amount of data, produce not only a better nominal model, but in addition generate a bound in the frequency domain that captures the presence of possible high-frequency model errors. Such bounding of model errors in the frequency domain is required by all nonadaptive design methods so as to ensure stability-robustness by limiting the bandwidth of the closed-loop system. Such identification algorithms do not exist in the classical identification literature; such questions were not even posed. Thus, we believe that is essential to develop such algorithms and then to incorporate them in the adaptive control problem.

Best Nonadaptive Compensator Design. Our research to-date has pinpointed the need for a good initial guess for an adaptive compensator, whose parameters are then updated by the adaptive algorithm. We are developing techniques that design the best (from the viewpoint of good command-following and disturbance rejection) nonadaptive compensator for the given prior plant uncertainty information. We do not know as yet how to design such nonadaptive compensators that exhibit this property of "best" performance-robustness. We are actively investigating this problem; its solution will provide us with the initial guess for the adaptive compensator. As relevant posterior information becomes available from the real-time sensor measurements, then the compensator parameters will be updated. At the very least, we shall then have a yardstick by which we can quantify the performance benefits that adaptive control will provide. With the present state of knowledge we never are sure how much performance improvement we can expect through the use of adaptive control. It is imperative that such comparisons can be made, because many adaptive control algorithms require external persistently exciting signals (which must be counted in the error budget) or slow sampling to achieve stability-robustness (whereby the low sampling rate may further deteriorate performance).

2. DIRECT NONLINEAR COMPENSATOR SYNTHESIS

Our long range goal in this project is to develop an integrated approach to nonlinear feedback control synthesis. The integration methodologies involve the blending of concepts and theories from (a) state-space representations, dynamic optimal control theory, and Lyapunov stability theory, and (b) from input-output operator-theoretic representations and conic-sector stability results.

The traditional method for designing a nonlinear feedback control system involves the linearization of the nonlinear dynamics at several operating conditions, the design of linear compensators at each operating condition, and finally the use of gain-scheduling to transform the family of linear compensators into a nonlinear one. What we are looking for are methods that bypass the linearization steps, and can yield directly a nonlinear dynamic compensator that meets the posed performance and stability-robustness specifications.

Our research philosophy in the area of nonlinear feedback control exploits the valuable lessons that we have learned during the past five years from the integration of time-domain and frequency-domain methods for **linear** feedback systems:

(a) Performance and stability-robustness specifications are most naturally expressed in an input-output context.

(b) The design of the dynamic compensator is most easily accomplished via a time-domain optimization-based algorithm, which should have guaranteed nominal-stability, and stability-robustness properties. However, the resultant control system need not be optimal in a well defined mathematical context.

(c) Any succesful design must lead to a compensator that creates an **approximate inverse** to the plant dynamics for the class of command-reference and disturbance inputs that dictate control system performance.

We have made significant progress in the development of such a direct design methodology for nonlinear systems. The structure of the nonlinear compensator involves a nonlinear model of the plant, together with nonlinear feedback loops inside the compensator. Thus we deal with a **Nonlinear Model Based Compensator (NMBC)**. We have exploited the structural and the mathematical properties of the NMBC and have shown that, under suitable mathematical assumptions, the NMBC dynamics can be modified using a **nonlinear loop-operator recovery (NLOR)** process.

It is worthwhile to note that at a high-level all the ideas behind the linear LQG/LTR design methodology can be extended to the nonlinear case. We refer to this methodology as NMBC/NLOR. Its use mimicks that of the linear case. Thus, given a nonlinear dynamic system one first defines a desired "target" nonlinear design that meets all specifications by solving a nonlinear dynamic optimal control problem that requires full-state variable feedback. We have transformed the properties of the nonlinear regulator into an input-output theoretic setting which sheds light into the guaranteed properties of the nonlinear loop, sensitivity, and closed-loop operators. Next, we have shown how to modify the dynamic characteristics of the NMBC, via the solution of an asymptotic nonlinear filtering problem, so that the nonlinear plant dynamics are inverted (approximately), and the desired "target" dynamics appear in all operators of interest.

Our progress to date is summarized in the paper by Grunberg and Athans, which was presented at the 1985 ACC. There are many hard theoretical details that remain to be straightened out, and these will be documented in Grunberg's Ph.D. thesis scheduled for completion in about a year. Nonetheless, a complete design methodology has been developed.

There are many obstacles that we see to the quick adoption of the NMBC/NLOR methodology for solving practical nonlinear control system design problems. In order to characterize the numerical values of the coefficients of the nonlinear differential equations of the NMBC/NLOR compensator, the designer must solve **off-line** two partial differential equations! One of these is the classical Hamilton-Jacobi-Bellman (HJB) equation arising from the definition of the "target" design nonlinear optimal control problem. The other partial differential equation is the mathematical dual to the HJB, and arises from the solution of a finite-dimensional nonlinear filtering problem. Needless to say, there do not exist reliable and numerically-robust subroutines for the routine numerical solution of partial differential equations of the HJB class. Nonetheless, the development of the NMBC/NLOR design methodology may provide the necessary motivation to invest resources for the numerical solution of HJB type equations in modern supercomputers. It may be worthwhile to recall that in the early 1960's the numerical solution of algebraic Riccati equations was considered a formidable task; today their solution is routine.

3. SYSTEMS WITH MULTIPLE SATURATION NONLINEARITIES

The goal of this project is to develop new methodologies for the analysis and synthesis of linear multivariable control systems that contain several saturation nonlinearities. We seek to develop modifications to the purely linear design methodologies, such as LQR, LQG, and LQG/LTR, to explicitly take into account the problems associated with multiple saturation nonlinearities in the control actuation channels.

There are several problems that can arise when a control system that has many saturation nonlinearities is designed by purely linear means. The most serious problem is that of stablility; it is possible for a control system, which is stable when the actuators are not saturated, to become unstable when one or more controls become saturated; the stability loss can happen if large command signals are applied or disturbances of large magnitude are present. The second class of problems are associated with performance. If the saturation limits are ignored in the purely linear design phase, it may happen that large crossover frequencies are specified by the designer. The saturating actuators may not be able to provide the gain necessary to attain the required bandwidths, and redesign must take place. The difficulty is that we do not have a systematic methodology which will help the designer specify rational bandwidths consistent with the different saturation limits. Also, transient performance suffers when saturation nonlinearities interact with integrators in the control loop; the so-called **reset windup** phenomenon. Reset windup keeps the nonlinearities saturated longer than necessary, and as a consequence transient responses are characterized by large overshoots.

What we would like to do is to examine these stability and performance problems associated with multiple saturations in a unified manner. In our research to date we have found that some common-sense simple ideas can have a major impact in performance. One such idea is to explicitly include the saturation nonlinearities in the LQG model based compensator; the resultant dynamic compensator is piecewise linear. Another idea relates to the adaptation of the simple "anti-reset windup" techniques for SISO systems to the MIMO case. Partial documentation along these lines can be found in the recent paper by Kapasouris and Athans presented at the 1985 ACC. However, we have only scratched the surface.

From a theoretical point of view we have found that it is possible to adapt the multivariable circle criterion to address stability issues; the proper use of the circle criterion yields reduced bandwidth designs. However, these can be quite conservative. It appears that directional information from the singular value decomposition must be used to reduce conservatism, perhaps coupled with reconfigurable dynamic compensators. Research is continuing along these lines.

4. FORWARD-SWEPT WING AIRCRAFT STUDIES

A multivariable control synthesis feasibility study, which is nearing completion, relates to the multivariable control of forward-swept wing aircraft, similar to the X-29. There are certain generic problems associated with the control of the longitudinal dynamics of such aircraft which arise from the highly unstable open-loop aircraft characteristics and flexure and torsional wing bending modes. We wanted to understand the interplay between the multivariable flight control system that must stabilize the inherently unstable airframe and the degree of modeling necessary associated with the wing bending modes.

Although we had obtained the X-29 rigid dynamics from Dreyden, we did not have any information on the flexible dynamics. For this reason, we decided to use a model of a forward-swept wing aircraft developed at Perdue University. The Perdue model is similar, but not identical, to the X-29 and it did include the first wing bending mode (at about 68 radians per second) and the first wing torsional mode (at about 270 radians per second). In the longitudinal axis one could control independently the canard and the flaperon control surfaces.

Studies by Honeywell Inc. on similar aircraft had posed the control of the longitudinal dynamics as a SISO problem, slaving the motions of the canard and the flaperon surfaces. We wanted to see what benefits, if any, could be obtained through independent dynamic control of the canard and flaperons. The physical flaperon characteristics are such that one cannot expect a large normal acceleration from their use, but it may be possible to use them in conjuction with the canard to independently control two longitudinal variables, the pitch attitude and the angle of attack, provided the commands were restricted to be small.

We employed the LQG/LTR methodology throughout. We found that in order to have any reasonable performance for the flight condition examined the closed-loop bandwidth must be about 10 rad/sec. As a consequence we had to explicitly model the wing bending mode, but we could ignore the wing torsional mode without experiencing instability problems.

In order to assess the potential benefits of independent flaperon control we designed three different control systems, two SISO ones and a two-input two-output (TITO) one using the same performance and stability-robustness specifications. One SISO design used only the canard to follow pitch commands. In the second SISO design we again used only the canard to follow angle-of-attack commands. In the TITO design we used both the canard and the flaperons to follow independent commands (small magnitude) in both pitch and angle-of-attack simultaneously.

We found that the flaperons can be quite effective in preventing the uncontrolled output in the SISO designs to drift off, while maintaining effectively the same performance for the control of the main variable. In the TITO design there was a very high degree of dynamic coordination between the canard and the flaperon surfaces. In other words, one does not lose anything by using the flaperons independently from the canard; there are benefits in a small signal environment from controling both pitch and angle of attack independently.

The documentation for this study will become available shortly in the M.S. thesis of Wilma Quinn.

5. TWIN-LIFT HELICOPTER SYSTEMS

Another feasibility study, that is still on going, relates to the automatic control of two helicopters jointly lifting a heavy mass, the so-called Twin Lift Helicopter System (TLHS). We became interested in studying these TLHS because of their importance to NASA and industry, and because they represent an extraordinarily complex multivariable control problem.

Our studies to date have only addressed the longitudinal control problem of the TLHS near hover. Realistic models of the Blackhawk helicopter were obtained with help from engineers at Sikorsky.

The TLHS is inherently a multivariable system. There are four controls that must be dynamically coordinated corresponding to the cyclic and collective controls for each helicopter. In principle, one can then control four independent outputs. In our studies we focused our attention to following commands in horizontal and vertical velocity, while explicitly regulating the load swing motion and the helicopter horizontal separation.

Our control system designs and evaluations are not as yet complete. Partial results indicate that the system is very hard to control, even under full automatic control. The difficulty arises because of three unstable poles and lightly damped minimum phase zeros. In order to rapidly attenuate any load motions, the helicopters must undergo significant pitching motions and changes in their vertical separation. For this reason, for applications of the TLHS in which precise control of the load position is necessary in the presence of significant wind disturbances, it may be advisable to consider independent control of the tether lengths in addition to the standard helicopter controls.

More details on the outcome of this study will be given in the next progress report.

6. PEOPLE

Professors Athans and Stein were appointed Associate Editors at Large for the IEEE Transactions on Automatic Control.

Professor Valavani was appointed Associate Editor of the IEEE Transactions on Automatic Control, and for the IFAC Journal AUTOMATICA.

PUBLICATIONS

The following publications have been supported in full or in part by NASA grant NAG 2-297 since its inception 1 June 1984. Copies of these publications have been transmitted to the grant monitors, NASA headquarters, and publications office as required.

1. D. M. Orlicki, L. Valavani, M. Athans, and G. Stein, "Adaptive control with variable dead-zone nonlinearities", Proc. American Control Conference, San Diego, CA, June 1984, pp. 1893-1898.

2. J. N. Tsitsiklis and M. Athans,"Guaranteed robustness properties of multivariable nonlinear stochastic optimal regulators", IEEE Trans. on Automatic Control, Vol. AC-29, August 1984, pp. 690-696.

3. D. M. Orlicki, " Model reference adaptive control systems using a dead-zone nonlinearity", LIDS-TH-1455, Ph.D. thesis, MIT, April 1985.

4. D. B. Grunberg and M. Athans, "A methodology for designing robust multivariable nonlinear feedback systems", Proc. American Control Conference, Boston, MA, June 1985.

5. P. Kapasouris and M. Athans, " Multivariable control systems with saturating actuators and anti-reset windup strategies", Proc. American Control Conference, Boston, MA, June 1985.

6. M. Bodson and M. Athans, " Multivariable control of VTOL aircraft for shipboard landing", Proc. AIAA Guidance and Control Conference, Snowmass, CO, August 1985.

7. G. Stein and M. Athans, "The LQG/LTR proceedure for multivariable feedback control design", accepted for publication in the IEEE Trans. on Automatic Control.