MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LABORATORY FOR INFORMATION AND DECISION SYSTEMS
CAMBRIDGE, MA 02139

STATUS REPORT #4

ON

NONLINEAR AND ADAPTIVE CONTROL

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SUBMITTED TO:

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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 May 30, 1986 to 31 December 1986. 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 complex high-performance 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 during this reporting period relate to the multivariable control of twin-lift helicopter systems. Significant progress in all areas has been accomplished during the past seven months.

1. ADAPTIVE CONTROL THEORY

Following the completion of the Ph.D. thesis by D. Orlicki's Ph.D. thesis, publication [3], our thinking about adaptive control has changed in a significant manner. 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. The new algorithms involve the real-time monitoring of easily measurable signals, and require the capability of computing discrete Fast Fourier transforms (DFFT's) 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 an 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 that research is a detailed appreciation of the immense complexity of the adaptive control problem. *In point of fact, we have become 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 questions that we have been investigating in the sequel.

Robust Adaptive Identification in the Time and Frequency Domains.

Research Goals. 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. This topic is being investigated by Mr. Richard LaMaire for his doctoral thesis, under the supervision of Professors Valavani and Athans.

Research Methodology. We view the robust adaptive control problem as a combination of a robust identifier (estimator) and a robust control-law redesign algorithm. Current robust control design methodologies, such as the LQG/LTR methodology, require: 1) a nominal model, and 2) a frequency-domain bounding function on the modelling error associated with the nominal model. A new robust estimation technique, which we call a 'guaranteed' estimator, is being developed to provide these two pieces of information for a plant with unstructured uncertainty and an additive output disturbance. This guaranteed estimator will use parametric time-domain estimation techniques to identify a nominal model, and non-parametric frequency-domain estimation techniques to identify a frequency-domain bounding function on the modelling error. This bounding function will be generated using discrete Fourier transforms (DFT's) of finite-length input/output data.

Several assumptions are required by the guaranteed estimator. In addition to a priori assumptions of the structure of the nominal model along with coarse, worst-case values of the parameters, we assume that the unmeasurable disturbance is bounded and that a magnitude bounding function on the Fourier transform of the disturbance is known. Further, we assume prior knowledge of a bounding function on the unstructured uncertainty of the plant relative to our choice of nominal model structure. These assumptions allow our time-domain estimator to be made robust to the effects of unstructured uncertainty and bounded disturbances. That is, our time-domain estimator updates the parameters of our nominal model only when there is good (uncorrupted) information. Similarly, the frequency-domain estimator, which is being developed, will only update the current bounding function on the modelling error when there is good information. In summary, the guaranteed estimator will provide a nominal model plus a guaranteed bounding function, in the frequency-domain, as to how good the model is. Accuracy guarantees in the identifier part of the adaptive controller can be used by the control-law redesign part of the adaptive controller to ensure closed-loop stability, assuming the control-law is updated sufficiently slowly.

Recent Research Progress: At present, all equations for this time-domain estimator have been developed. The maximum possible effect, in the plant output, due to the unstructured uncertainty and the disturbance is computed using real-time DFTs of the input and the a priori assumed bound on the disturbance. The identification algorithm only updates the parameter estimates when the output error between the actual and predicted plant output is greater than the maximum possible error signal due to the unstructured uncertainty and the disturbance.

The previously described frequency-domain estimator is currently also complete, and its interface with the time-domain fully developed. The DFTs of the input/output data are used to compute a frequency-domain estimate of the plant. Then, the a priori assumption of a magnitude bound on the Fourier transform of the disturbance is used by the frequency-estimator to provide an uncertainty bounding function on the frequency-domain estimate of the plant.

Additional issues concerning the guaranteed estimator relate to the fact that we are estimating a continuous-time plant with a discrete-time estimator. For example, the choice of sampling period for the estimator limits both the bandwidth of the adaptive control system as well as the accuracy of the estimator at high frequencies.

All the equations necessary to simulate the performance of these identification algorithms are being coded and debugged. Because of the extensive real-time spectral calculations, we have decided to use the CYBER supercomputer at Princeton which is available for use by the MIT community at no cost for CPU time. A numerical example which is simple enough to demonstrate the ideas yet rich enough to capture the potential pitfalls has been designed.

The structure of these robust identification algorithms is very complicated. Several approximations were required so as to implement them, and such approximations are invariably accompanied by a certain degree of conservatism to meet the stability-robustness constraint. We hope that these conservative approximations will not have a serious impact upon the performance of the algorithm. This is the reason that we have to invest a great deal of effort in carrying-out and analyzing the digital computer simulations.

At any rate, it is becoming increasingly self-evident that to design adaptive control systems for practical systems (which have significant dynamic modeling errors and are subject to unmeasurable disturbances) requires extensive real-time spectral calculations in order to provide iron-clad guarantees that the adaptive feedback system will be closed-loop stable. At the end of this doctoral thesis, on the basis of the performance of the simulations and real-time requirements, we plan to reevaluate our plan of attack with respect to adaptive control research.

Documentation Status: No formal documentation on this research is available as yet. The Ph.D. thesis of Mr. LaMaire is scheduled for completion in the summer of 1987.

Best Nonadaptive Compensator Design for Performance-Robustness.

Research Goals. 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.

Research Methodology. In his doctoral research Mr. David Milich, under the supervision of Professors Athans and Valavani, is developing a design technique which will yield the "best" fixed-parameter nonadaptive compensator for a plant characterized by significant structured, as well as unstructured, uncertainty. The "best" compensator is defined as the one that meets the posed performance (i.e. command-following, disturbance-rejection, insensitivity to sensor noise) specifications and stability-robustness over the entire range of possible plants.

This robust design technique will prove useful in a number of ways. First, it will yield a systematic procedure for designing feedback systems for uncertain plants with performance guarantees. Thus, the feedback loop will be guaranteed to be stable and, in addition, will meet minimum performance specifications for all possible plant perturbations.Second, the solution of this robust design problem will also enable us to quantitatively address one of the most fundamental questions in adaptive control: *what are the performance benefits of adaptive control?* While much attention has been paid to the development of many specific adaptive algorithms, very little consideration has been given to this issue at the heart of the adaptive control problem. Practical adaptive systems rely upon external persistently exciting signals (to ensure good identification), slow sampling (which helps stability-robustness to unmodeled high frequency dynamics) in addition to extensive real-time computation (to provide safety nets and turn-off the adaptive algorithm when it exhibits instability). All these "gimmicks" degrade command-following and disturbance-rejection performance and tend to neutralize the hoped-for benefits of an adaptive compensator. In light of these circumstances it is imperative that the decision to use adaptive control, for a real engineering application, must be based upon a quantitative assessment of costs and benefits. One of the main goals of this research project is to quantitatively evaluate the performance benefits of an adaptive control system vis-a-vis the best fixed-parameter nonadaptive compensator for a linear plant. Note that for a nonlinear system the parameters of such compensators can be fine-tuned using gain scheduling.

While a performance-robust design methodology will be useful in its own right, the positive implications for adaptive control should be clear. It is conjectured that such a fixed-parameter compensator design technique will form the basis of a practical robust adaptive control system. Compensator redesign will take place infrequently (when compared to the digital sampling rate) using information from a reliable system identification scheme.

Some of the key issues in the design process have been identified. The design will take place using frequency domain concepts since performance/robustness tradeoffs exist at each value of frequency, as well as over the entire frequency spectrum.

We visualize the performance-robust design process to consist of three basic steps. First, the "best" design plant must be found from the set of all possible plants; the information in the Nyquist diagram has been found useful in our preliminary studies. Second, the design plant model is used in conjuction with the LQG/LTR or H-∞ optimization methodology to perform the nominal control system design. Third, the nominal compensator will be augmented with suitable dynamics which will ensure stability-robustness and robust-performance of the feedback system.

Recent Research Progress. Conditions for stability-robustness and performance-robustness in the presence of significant structured and unstructured uncertainty have been developed. An a-priori magnitude bound, as a function of frequency, on the unstructured uncertainty is assumed known. In order to reduce the conservatism of the stability and performance conditions with respect to the structured uncertainty, directional information (in the complex plane) associated with the plant-parameter variations is exploited. Unfortunately, this directional information turns out to be closely associated with the so-called *Real-μ problem*, i.e. the problem of calculating real structured singular values; this problem has been studied by Doyle and is generically very difficult.

Another recent result relates to the fact that the "best robust compensator" will have to be infinite-dimensional. Thus, from a pragmatic point of view, *we may have to use a very high-order dynamic compensator in order to "squeeze-out" the best possible performance from a highly uncertain plant.* This tentative conclusion raises some serious questions regarding the implementation of this compensator. Another critical issue is related with the use of this compensator within an adaptive control context. Presumably the posterior information generated by the real-time identification algorithm will be used to update the compensator parameters. If the "best" compensator is of very high order, much larger than the order of the plant, then new adaptive parameter-update algorithms will have to be developed. We speculate that the computational complexity of these, as yet undefined, adaptive algorithms will be far greater than those suggested in the past -- e.g. model reference adaptive control.

Documentation Status. Only partial documentation exists [20] for this research. The Ph.D. thesis of Mr. Milich is scheduled for completion in the winter of 1987-1988.

2. NONLINEAR CONTROL SYSTEMS.

A significant portion of the grant resources is devoted to the development of methodologies, theories, and design techniques that will advance the state of the art in multivariable control system design. During this reporting period we have made some significant advances in the theory of nonlinear feedback systems.

Direct Nonlinear Control Synthesis Using the NMBC/NLOR Method.

With the recent completion of D. B. Grunberg's doctoral thesis [20], we have completed a major milestone in this area.

Research Goals. 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.

Research Methodology. 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.

Recent Research Progress. Mr. D. B. Grunberg, in his doctoral research under the supervision of Professor Athans, has developed 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. We refer to this methodology as NMBC/NLOR.

We have shown that under some, not very restrictive, assumptions the *Extended Kalman Filter* (EKF) is guaranteed to be a good estimator in the nonlinear control context, because - just as the linear Kalman Filter -- the EKF has certain guaranteed stability and, more important, robustness properties. Thus the EKF can be used to design a *Filter Operator Loop* (FOL) which can serve as the "target" designs in the NMBC/NLOR context.

We have also shown that if the nonlinear plant is in, or can be transformed to, the so-called *controller and observer form,* we can easily carry out the NLOR process in which asymptotically the loop operator of the nonlinear feedback control system approaches the FOL. In fact, the NMBC/NLOR process when applied at the plant input, where we are trying to recover the desirable characteristics of a full-state feedback design based only on limited output measurements, works even if the nonlinear plant is *only* in the so-called controller form .

The theoretical results have been illustrated using a simple nonlinear pendulum to carry out numerical simulations and evaluations.

Documentation Status. Our progress to date is summarized in two papers by Grunberg and Athans; see publications [4] and [15]. Full documentation can be found in Grunberg's recently completed Ph.D. thesis [20].

Systems with Multiple Saturation Nonlinearities.

Research Goals. The goal of this project is to develop new theory and 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, LQG/LTR, and H-∞ optimization, 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 stability; 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.

Research Methodology. What we plan to do is to examine these stability and performance problems associated with multiple saturations in a unified manner. Most of the existing theory is either too complex or incomplete. It is possible to deal with saturation nonlinearities using optimal control theory, and derive necessary conditions using Pontryagin's maximum principle; unfortunately, this only provides us with open-loop solutions through the solution of complex two point boundary value problems for high-order plants. Most other approaches are based upon Lyapunov theory, which does not capture in a straightforward way the input-output behavior necessary for design.

This research is carried out by Mr. Petros Kapasouris as part of his Ph.D. thesis, under the supervision of Professor Athans.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.

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. For SISO systems we have found what appears to be a less conservative approach. Research is underway to extend these ideas to the MIMO case. It appears that directional information from the singular value decomposition must be used to reduce conservatism, perhaps coupled with reconfigurable dynamic compensators.

Recent Research Progress. During this reporting period we were able to come up with a simple, yet elegant, way of attacking the problem. This idea appears to have a great deal of promise. The underlying concept is to have the command-following response of the MIMO system mimick, to the extent possible by the presence of the saturation nonlinearities, the transient response of the linear system. The idea is to monitor and adjust in real-time the output of the dynamic compensator so that it never generates signals that will drive the system into saturation. In this manner, we are able to maintain the necessary "directional" properties of the design which are required to carry-out the *approximate plant inversion* and substitution of the "desired" dynamics in the forward loop. Note that if we allow arbitrary saturation of the nonlinearities, the directional properties of the linear design become distorted; as a consequence, we destroy the approximate plant inversion property of our compensator. The method under study controls the signal levels so that the system always works in the linear region. *This key idea appears to solve all at once the undesirable stability, performance, and reset-windup issues.* Of course, as to be expected, the speed of response (rise time, settling time etc) to commands of large magnitude is reduced compared to the design without saturation nonlinearities.

For stable open-loop plants, this procedure can be implemented by a nonlinear transformation on the error vector, which drives the compensator. Thus, we are using a nonlinear feedback channel around the otherwise linear compensator. For open-loop unstable plants, we must be careful so as to limit the rate of large command signals, and this requires that a command-shaping nonlinearity be introduced at the command-reference channels.

What remains is to work out carefully all the necessary mathematical proofs, and test the algorithm using several examples.

Documentation Status. Partial documentation of earlier research can be found in the paper by Kapasouris and Athans [5]. Full documentation will be found in Kapasouris' doctoral thesis, scheduled for completion in September 1987.

Gain Scheduled Control Systems

Gain scheduling is a common engineering method used to design controllers for systems with nonlinear and/or parameter varying dynamics. In the nonlinear case, the dynamics are linearized at several operating points, and a linear compensator is designed for each linearized plant. The parameters of the compensator are then interpolated, or scheduled, in between operating points, thus resulting in a global compensator. The procedure for linear parameter varying dynamics is identical to that above, except that the linearization is omitted.

Research Goals. Despite the lack of a sound theoretical foundation, gain scheduling has proven successfull in many engineering applications (e.g. jet engines, submarines, and aircraft). A goal of this project is to develop such a theoretical treatment of gain scheduled control systems. However, the ultimate goal is to use this analysis for the development of a complete and systematic gain scheduling design methodology. Given the success of current gain scheduled designs, such a development would prove very useful in better understanding and strengthening gain scheduled designs.

Research Methodology. Initial research has been directed at the linear parameter varying case in the doctoral research of Mr. Jeff Shamma, under the supervision of Professor Athans. An initial obstacle in the study of parameter varying, hence time varying, linear systems is that traditional linear time invariant analysis methods, in particular singular value loop shapes, are not immediately applicable. That is to say, if one designed a parameter varying compensator such that each "frozen parameter" design satisfied certain design specifications, there is no guarantee that the resulting time varying design will even be stable, let alone satisfy performance specifications. However, using input/output operator methods and conic sector stability results, some progress has been made in extending the notions of singular value loop shapes to time varying systems, thus significantly simplifying the analysis of closed loop feedback properties, e.g. sensitivity, robustness, etc.

Research was also conducted on how one should schedule the parameters of the compensator in between operating points. Initial results have shown that selection of the right parameterization of the compensator can yield an interpolation strategy which guarantees nominal stability in between operating points, *and* is apt to pick up any trends in design specifications which vary over the parameters. The key idea is that the design parameters, rather than the physical compensator parameters, are best suited for capturing the different specifications over the range of parameter variations. In particular, it has been shown that the LQG/LTR compensator is very well suited for such a parameterization since it provides enough a priori structure to the compensator to allow for a simple parameterization of compensator designs, while giving enough flexibility to satisfy design specifications.

Recent Research Progress. A great deal of effort was devoted into understanding the stability-robustness properties of linear time-varying systems due to unmodeled time-invariant dynamics. As mentioned above, gain-scheduled designs, with slow parameter variations, can be modeled as linear time-varying systems. Thus, it is important to develop sufficient conditions for stability in the presence of unmodeled dynamics. Such expressions have been derived and at present are being analyzed.

Documentation Status. No documentation of this research is available as yet. Mr. Shamma's doctoral thesis is scheduled for completion in 1988.

3. FEASIBILITY STUDIES

As mentioned before a small portion of the resources of this grant are devoted to the design of multivariable control systems for aerospace systems that are of direct interest to our NASA sponsors. These feasibility studies serve as a means for understanding the strengths and weaknesses of the theoretical results developed under the auspices of this grant. During this reporting period we only had a single active project in this area.

Twin-Lift Helicopter Systems.

Research Goals. A multivariable control synthesis feasibility study, which has just been completed and documented in the SM thesis of A. Rodriguez [14], relates to to the development of an automatic flight control system (AFCS) for two helicopters jointly lifting a heavy payload. We became interested in studying the so-called Twin Lift Helicopter System (TLHS) because of its importance to NASA and industry, and because it represents an extraordinarily complex control problem.

Research Methodology. For simplicity our study focussed only on the longitudinal rigid body dynamics of the TLHS near hover. A seven degree of freedom (three per helicopter; one for load) linear model was used throughout the research endeavour. The helicopters modeled were Sikorsky UH-60A Blackhawks.

Since our study focussed on the planar dynamics, only four controls (two per helicopter) were relevant. These controls, of course, were the helicopter cyclic pitch controls and collective pitch controls. Because we had four independent controls, we could independently control at most four outputs. Throughout the study, we focussed our attention upon following commands in horizontal and vertical velocity, while explicitly regulating the motion of the payload and the horizontal separation between the helicopters.

We examined two versions of the problem. The simplest case assumes that the tether lengths are equal. Under this assumption, it is possible to find a coordinate system in which the 4-input 4-output multivariable control design problem splits into three separate design problems: two SISO designs and one 2-input 2-output design. The more complex case assumes that the tether lengths are not equal, so that at equilibrium the helicopters are at different altitude. In this case, we have one SISO design problem and one 3-input 3-output design problem.

Recent Research Progress. The results of the research indicate that the TLHS is very hard to control, even under full automatic control. The difficulty arises from several sources. One source of difficulty is attributable to three unstable poles associated with the longitudinal configuration. Because of these unstable poles any AFCS would require a minimum bandwidth just to stabilize the system. This minimum bandwidth would be accompanied by minimum pitch rates and control rates (for fixed reference commands). These rates, of course, depend on the amplitude and spectral content of the applied reference commands and of disturbances. Based on these facts alone one might conjecture that pre-filtering of references, so as to command smooth transitions, would be necessary in order to ensure "passenger friendly" pitch rates and realistic control rates. In order to keep these rates reasonable we kept the bandwidth of the closed loop system near the minimum.

Another source of difficulty arises from the presence of three lightly damped pole-pairs which lie within an octave of the minimum bandwidth required to stabilize the system. Because of the large phase lag which these poles contribute near crossover, it follows that to have nice robustness properties we require a great deal of lead. Although this lead helps with stability robustness, it requires quite large pitch and control rates, even when "reasonable" sudden step-commands are suddenly applied for all four outputs simultaneously. In fact, it was found that as our robustness properties improved, the control effort required increased rapidly. This implies that we must trade-off robustness for "reasonable" controls. It is this trade-off which makes the Twin Lift control problem so difficult.

In summary, the research has confirmed our physical intuition about TLHS dynamics. In order to rapidly attenuate any load motions, the helicopters must undergo significant pitching motions and rapid changes in their vertical separations. Because of this we feel that for applications of the TLHS in which precise control of the load position is necessary in the presence of significant wind disturbances, we believe that additional research be carried out to more fully understand how to best control such TLHS along all axes, including studies that are directed toward the cost/benefit tradeoffs associated with active tether control to control "easier" the motion of the suspended mass without adverse motion of the helicopters as in the present design.

Documentation Status. Partial documentation of this research can be found in publication [13]. The full documentation for this study is available in the S.M. thesis of A. Rodriguez [14].

PEOPLE

Professor Michael Athans received the *Outstanding Paper Award* of the IEEE Control Systems Society for the paper, co-authored with John N. Tsitsiklis, "On the Complexity of Decentralized Decision Making and Detection Problems," which was published in the IEEE Transactions on Automatic Control, Vol. AC-30, No. 5, May 1985. The award was presented on December 11, 1986 during the 25th IEEE Conference on Decision and Control, Athens, Greece.

Professor Lena Valavani was reappointed Associate Editor of the IEEE Transactions on Automatic Control. She was also reappointed Associate Editor of the IFAC journal AUTOMATICA.

Professor Michael Athans was elected for a three-year term to the nominating committee of the Engineering section of the American Association for the Advancement of Science (AAAS).

Dr. Daniel B. Grunberg presented the results of his Ph.D. thesis at a seminar at NASA Ames Research Center in October 1986. Dr. Grunberg, following the receipt of his Ph.D. degree from MIT, joined the staff of ALPHATECH Inc., Burlington, Mass.

Ms. Wilma W. Quinn, following the completion of her MS thesis, joined the staff of the General Electric Co., Lynn, Mass.

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, Cambridge, Mass., 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, pp. 1588-1595.

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, pp. 1579-1584.

6. M. Bodson and M. Athans, " Multivariable Control of VTOL Aircraft for Shipboard Landing," *Proc. AIAA Guidance, Navigation and Control Conference,* Snowmass, CO, August 1985, pp. 473-481.

7. G. Stein and M. Athans, "The LQG/LTR Procedure for Multivariable Feedback Control Design," LIDS-P-1384, accepted for publication in the *IEEE Trans. on Automatic Control,* Vol. AC-32, No. 2, February 1987.

8. G. Stein, "Beyond Singular Values and Loop-Shapes," LIDS-P-1504, MIT, Cambridge, Mass., January 1986.

9. M. Athans, P. Kapasouris, E. Kappos, and H. A. Spang III, "Linear-Quadratic-Gaussian with Loop-Transfer-Recovery Methodology for the F-100 Engine," *AIAA Journal of Guidance, Control, and Dynamics,* Vol. 9, No.1, January 1986, pp. 45-52.

10. M. Athans, "A Tutorial on the LQG/LTR Method," *Proc. American Control Conference,* Seattle, Wash., June 1986, pp. 1289-1296.

11. W. H. Pfeil, M. Athans, and H. A. Spang III, "Multivariable Control of the GE T700 Engine using the LQG/LTR Design Methodology," *Proc. American Control Conference,* Seattle, Wash., June 1986, pp. 1297-1312.

12. W. W. Quinn, "Multivariable Control of a Forward Swept-Wing Aircraft", MS Thesis, LIDS-TH-1530, MIT, Cambridge, Mass., January 1986.

13. A. Rodriguez, "Multivariable Control of Twin Lift Helicopter Systems using the LQG/LTR Design Methodology," MS Thesis, MIT, Cambridge, Mass., January 1987.

14. A. Rodriguez and M. Athans, "Multivariable Control of a Twin Lift Helicopter System Using the LQG/LTR Design Methodology," *Proc. American Control Conference,* Seattle, Wash., June 1986, pp. 1325-1332.

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