GEORGIA INSTITUTE OF TECHNOLOGY **OFFICE OF CONTRACT ADMINISTRATION**

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-16-676 R5930-0A0 (Sub-Project is E-25-N01) GTRC/GIT DATE 8 / 7 / 85

Project Director: D.P. Schrage School/Lab AE

Sponsor: Hughes Helicopters, Inc. Centinela and Teale Streets
Culver City, CA 90230

Type Agreement: P.O. No. 263841 and Standard Agreement Dated 4/11/85

Award Period: From 1/1/85 To 12/31/87 (Performance) 12/31/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$
Funded:	$ 12,467.00	$ 12,467.00

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: Design Of A Helicopter Automatic Flight Control System

ADMINISTRATIVE DATA OCA Contact R. Dennis Farmer X4820

1) Sponsor Technical Contact:

Mr. Phil Fitzsimons
Hughes Helicopters, Inc.
Building 6, M/S C209
Centinela and Teale Streets
Culver City, CA 90230
(213) 305-5408

2) Sponsor Admin/Contractual Matters:

Mr. Al Ewing
Hughes Helicopters, Inc.
Building 12, T50
Centinela and Teale Streets
Culver City, CA 90230
(213) 305-4410

Defense Priority Rating: ______ Military Security Classification: ______
(or) Company/Industrial Proprietary: ______

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with NONE PROPOSED.

COMMENTS:

COPIES TO: SPONSOR'S I. D. NO. 02.207.000.85.006

Project Director
Research Administrative Network
Research Property Management
Accounting

Procurement/GTRI Supply Services
~~Research Security Services~~
Reports Coordinator (OCA)
Research Communications (2)

GTRC
Library
Project File
Other Jones

12/88

N-1 ... SR 5

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Date 5/11/89

Project No. E-16-676 Center No. R5930-0A0

Project Director D. P. Schrage School/Lab AE

Sponsor McDonnell-Douglas Helicopter Co.

Contract/Grant No. 263841 GTRC XX GIT ___

Prime Contract No. ___

Title Design of Helicopter Automatic Flight Control System

Effective Completion Date 12/31/87 (Performance) 12/31/87 (Reports)

Closeout Actions Required:

___ None
___ Final Invoice or Copy of Last Invoice
_x_ Final Report of Inventions and/or Subcontracts_ Patent questionnaire sent to P/I.
___ Government Property Inventory & Related Certificate
___ Classified Material Certificate
___ Release and Assignment
___ Other ___

Includes Subproject No(s). *E-16-526/ E-25-N01 /*T-87-393
Not in DB//Tongue/ME// Not in DB

Subproject Under Main Project No. ___

Continues Project No. ___ Continued by Project No. ___

Distribution:

_X_ Project Director
_X_ Administrative Network
_X_ Accounting
_X_ Procurement/GTRI Supply Services
_X_ Research Property Management
___ Research Security Services

_X_ Reports Coordinator (OCA)
_X_ GTRC
_X_ Project File
_2_ Contract Support Division (OCA)
_X_ Other E-25-N01

*No Record of these Projects

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

November 14, 1986

MEMORANDUM

TO: Director
Office of Contract Administration
ATTN: Mr. Don Hasty

FROM: D.P. Schrage, Professor
School of Aerospace Engineering

SUBJECT: Annual Report, Project # E-16-676, for
Sponsor McDonnell Douglas Helicopter Company

1. Attached are two copies of material which constitutes the annual report per subject sponsored project.

2. In addition to material provided, an additional briefing was given to sponsor at Georgia Tech in December 1985.

DPS/ln
Attachments

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING

November 13, 1986

MEMORANDUM

TO: R.B. Gray, Acting Director
School of Aerospace Engineering

FROM: D.P. Schrage, Professor
School of Aerospace Engineering

SUBJECT: Overdue Deliverables, Project No. E-16-676

1. This project is in the second year of a planned three-year project which involves a graduate co-op student, Mr. Philip Fitzsimons, who spent most of the first year at the sponsor's facility, McDonnell Douglas Helicopter Company in Tempe, Arizona. This is a joint project between the Schools of Aerospace and Mechanical Engineering. The project is funded by the sponsor as an IRAD project. The annual report for the first year's effort was included in the proposal for the second year which is included as Enclosure 1.

2. During the second year, this year, periodic reports have been provided using the sponsor's IRAD format. Reports submitted thus far are included as Enclosure 2. A briefing was also given at the sponsor's facility on September 1986 summarizing the results of the project to date and seeking direction on future efforts.

DPS/rm
Enclosures

ENCL 1

GEORGIA TECH RESEARCH CORPORATION

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0420

Telex: 542507 GTRCOCAATL
Fax: (404) 894-3120

Phone: (404) 894-4817

Refer to: JLG/02.212.000.86.004

18 February 1986

McDonnell Douglas Helicopter Company
4645 S Ashe Ave.
Tempe, AZ 85282

Attention: Dr. D. Banerjee

Subject: Research Proposal Entitled, "Design of a Helicopter Automatic Flight Control System"

Gentlemen:

The GEORGIA TECH RESEARCH CORPORATION is pleased to submit herewith the subject proposal prepared by D. P. Schrage Professor, of Aerospace Engineering, Georgia Institute of Technology. The program to be undertaken, the time required, and the estimated costs of the program are discussed in the proposal. We are also enclosing for your review three copies of our standard research project agreement we propose using for this project.

You will note that this agreement is a cost-reimbursement, no profit, no loss type under which you will be invoiced in accordance with the effort actually applied against the project. Funds authorized will not be exceeded without your express permission. In the event the full amount is not required to reimburse our expenses, the savings accrue to you. The agreement also contains a provision giving you the right to terminate the project on ten days written notice to us.

The Georgia Tech Research Corporation is a non-profit, non-endowed organization and must minimize its working capital requirements through advance payments by sponsors. Accordingly, the proposed research will require an advance payment of $3,000. A provisional invoice for the advance payment is enclosed should you desire to use it. Monthly invoices will be rendered and are due and payable within fifteen days of invoice date. The advance payment will be applied against the final invoice and any remaining balance will be refunded at the end of the project. A check for the advance payment should accompany your authorization to perform this project.

If you have any questions or desire additional information in connection with this proposal, please do not hesitate to contact us. Matters relating to the technical program may be referred to D. P. Schrage at 404/894-6257. Contractual and business matters should be referred to the undersigned at 404/894-4817.

Should the attached proposal and agreement meet with your approval as prepared, please insert your state of incorporation, sign, and return two copies of the agreement to this office. The agreement will then be signed on behalf of the GTRC, a research project number assigned, and one fully executed copy returned for your file.

We appreciate the opportunity of submitting this proposal and look forward to the possibility of working with you on this project.

Sincerely,

Jerry Goldbaugh
Contracting Officer

JLG/cfd

Addressee: In triplicate
Enclosure: Proposal - in triplicate
Agreement - in triplicate
Invoice No. 022486/02.212.000.86.004

Research Proposal

Submitted to

McDonnell Douglas Helicopter Company

DESIGN OF A HELICOPTER AUTOMATIC FLIGHT CONTROL SYSTEM

February 7, 1986

D. P. Schrage, Professor
School of Aerospace Engineering
Principal Investigator

W. M. Sangster, Dean
College of Engineering

A. L. Ducoffe, Director
School of Aerospace Engineering

J. L. Goldbaugh
Contracting Officer

Proposal Update for Second and Third Years
"Design of a Helicopter Automatic Flight Control System"

1. INTRODUCTION

The original subject proposal was for a three year effort to design a helicopter automatic flight control system based on the application of parameter identification techniques and the use of optimal control theory to develop an adaptive controller. This work is continuing but needs further clarification based on personnel and priority changes at MDHC which resulted in a change in the graduate co-op's company advisor and his reassignment to another area. Also, the budgets for the second and third years have been revised to include the graduate co-op's fellowship in the contract. In previous discussions during the initial contract's negotiations this was to be handled outside of the contract. A systems approach to rotocraft stability and control research is being applied in this effort and the methodology is illustrated in Figure 1.

2. REVIEW OF FIRST YEAR EFFORTS AND RECOMMENED CHANGES FOR YEARS TWO AND THREE

The tasks to be accomplished during year one are included as Attachment 1. Even with the change in the graduate co-op's supervisor and his reassignment to another area, most of the year one tasks were accomplished. These results are summarized in Attachment 2. Since returning to Georgia Tech this quarter he has obtained and installed CTRL-C on the VAX computer and has written least squares and extended Kalman filter algorithms for use in parameter identification. He has given a seminar on his research to the Center of Excellence in Rotary Wing Aircraft Technology (CERWAT) faculty and students. He has also ordered the Symbolic Manipulation Program (SMP) for use in his continued research. Next spring at the AHS Forum in Washington, D. C. he will be co-authoring a paper on system identification techniques which will be given as part of a panel on "System Identification and Its Applications for Rotorcraft".

While it is proposed to accomplish the year 2 and year 3 tasks as outlined in Attachment 1, some clarification is required. CERWAT has recently acquired a generic helicopter stability and control mathematical model, called ARMCOP, from NASA Ames Research Center. This model has been used by the Army and NASA to conduct real time and non-real time piloted simulation of the UH-60A Black Hawk Helicopter and AH-1G Cobra Helicopter. It is proposed to use this generic ten degree-of-freedom model as a reduced order model for comparison with Flyrt and Triplm. Initially, it is planned to model the current Hughes 369 F helicopter for use in parameter identification and control algorithm development. This approach is recommended for several reasons. First, the 369F is a relatively simple helicopter without a sophisticated automatic flight control system, thus preventing an inordinate amount of time trying to model a very complex helicopter. Second, the results obtained for this helicopter in adaptive control system design can be applied to more complex helicopters, such as the AH-64 or LHX. Finally, it is envisioned that future evolutions in this light helicopter field will require more trade-offs during the design phase between the control system and other areas, thus making this information valuable to MDHC. Another clarification to address is the availability of handling qualities data and its comparison with required criteria. Recently, helicopter flying qualities specification, MIL-8501A, has been revised for the LHX RFP. It is proposed to use this new criteria in conducting the proposed research. Available flying qualities test data and simulation results on Hughes' light helicopters i.e. 369 or OH-6 will be required for comparison purpose as this research evolves. With this clarification we propose to accomplish the year 2 and 3 tasks identified in Attachment 1.

3. <u>UPDATE BUDGETS for YEAR 2 and YEAR 3</u>

Based on including the graduate co-op fellowship in the contract and the adjustments in Georgia Tech's overhead and Retirement Benefits rates the year 2 and year 3 budgets have been revised and are included as attachment 3. An additional point to be emphasized is the leveraging that MDHC enjoy's on this particular contract. Dr. Benson H. Tongue, one of the principal investigators (P.I's) on this contract, has been awarded a NSF Presidential Young Investigator's Award. Under this award the NSF will put up one dollar for every sponsored research dollar the Young Investigator brings in. The overall benefit to MDHC under this arrangement is that for every two dollars of sponsored research you provide approximately three dollars is directly applied to the actual research, with one dollar covering overhead and retirement benefits. This is significant when compared with actual usage of most project research dollars.

The research program in Rotary Wing Flight Mechanics and Controls is built around the following theme:

A SYSTEMS APPROACH TO ROTORCRAFT STABILITY AND CONTROL RESEARCH

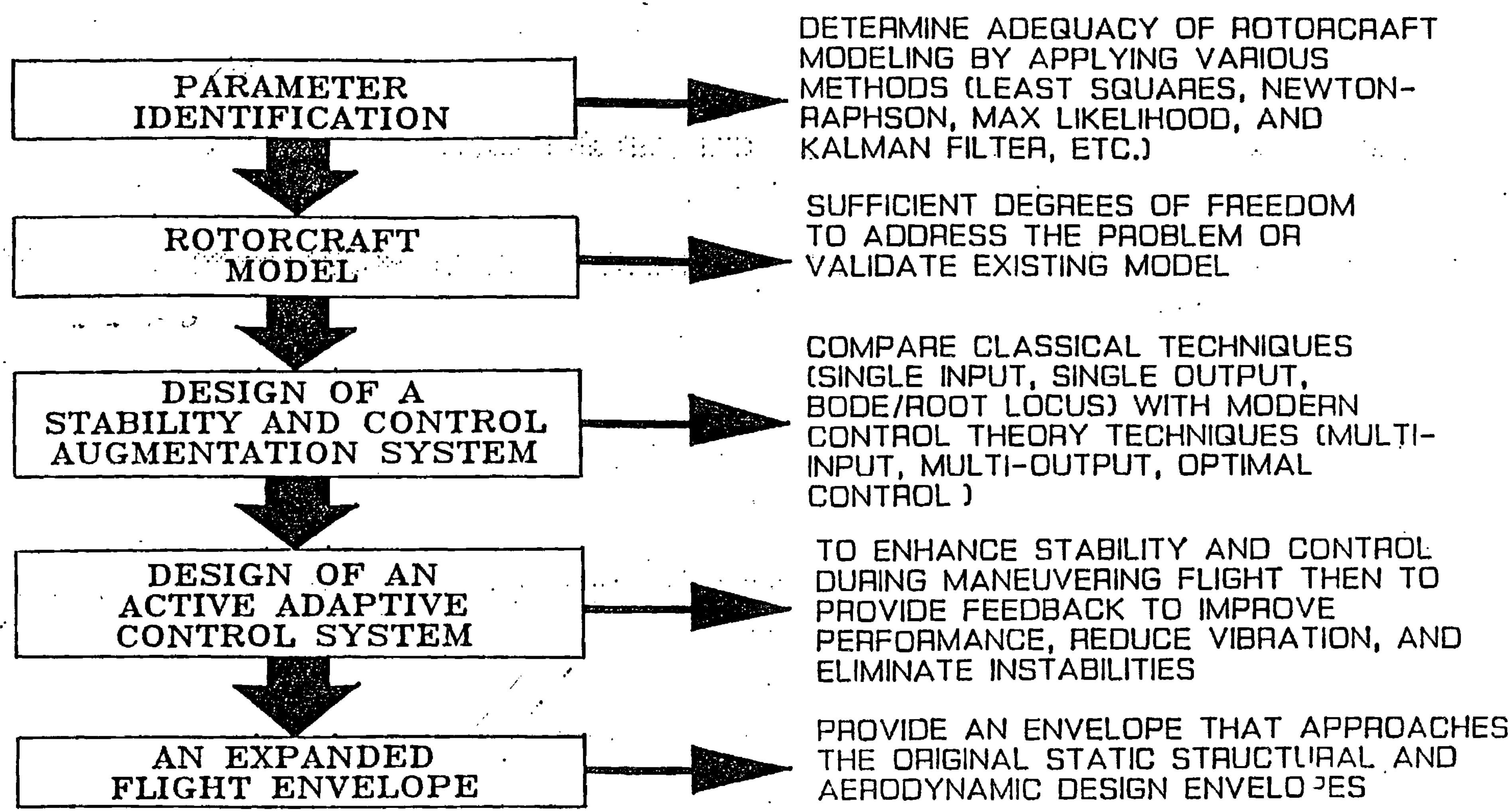


FIGURE 1

Tasks

Year 1

(a). Become proficient with Flyrt and Triplm.

(b). Develop a six degree-of-freedom reduced order model.

(c). Identify system control parameters by means of:

(i) Kalman Filtering
(ii) Recursion
(iii) Maximum Likelihood
(iv) Other

(d). Apply results of part (c) to:

(i) Hover
(ii) Cruise at 120 knots for predetermined inputs

(e). Publish Paper.

Year 2

(a). Combine all available handling qualities data into a statistically presentable form.

(b). Use part (a) to help generate a mathematical model that yields the "optimal" handling qualities.

(c). Publish Paper.

Year 3

(a). Determine the penalty matrices required to allow the actual system to track the optimal model.

(b). Determine how much of the optimal regulation problem can be solved on-line.

(c). Determine the best adaptive control strategy to connect the steady state flight regimes to allow acceptable control throughout the flight envelope.

(d). Publish Paper.

Summary of Graduate Co-op's
Efforts While at MDHC, Sept 84 to Sept 85

On June 1, 1985 Philip FitzSimons transferred from the Flight Controls Group into the Aeromechanics section headed by Dr. Bob Wood to work under the direction of Dr. Friedrich Straub. He has been supported by the HHC/Ground Resonance project. Following is a brief Synopsis of the work he has done over the Summer.

Initially, he was asked to review and extend the work that Dr. Straub had done in researching the usefulness of active control to suppress ground resonance. Realizing the amount of Algebra that went into the problem formulation it was decided that the use of Symbolic Manipulation Programs would be very useful in developing an improved analytical model. Three programs were considered MACSYMA, REDUCE, and SMP. It was decided to bring the REDUCE program in-house and install it on the IBM 3031 due to its low cost and the familiarity of some of the members of the Aeromechanics section with its use. A long term plan to bring SMP in-house for future work is currently being considered by Dr. Straub.

Another area of interest covered by the HHC/Ground Resonance project is Parameter Identification. This is the area where the most work was done by Mr. FitzSimons due to his interest in adaptive controls. Following is a brief description of the work he did.

First, a program was written using CTRL-C to implement a Least Squares and an Exponentially Weighted Least Squares Identification of a linear discrete time process. The dynamic models used were two linearized stability models of the AH-64. One was for Hover and the other for 130 knots. The purpose of the identification was to predict the elements of the state transition matrix and the control distribution matrix (A and B, respectively). The performance of the Identification algorithms with different noise levels and unmodelled high frequency dynamics was investigated. The results from the simulations are attached. It was found that the performance of the Identification algorithms in the prescence of noise was not very good. This is due to the fact that the parameter estimates are statistically biased. Although they are assymptotically unbiased, the convergence of the estimated parameters to the true parameter values is very slow. The variance of the errors can be shown to decrease with the square root of the number of measurements taken. The performance of the Identification with unmodelled high frequency dynamics and without noise is good. The high frequency dynamics were put in series with the basic stability model to simulate rotor dynamics. Since the zero frequency gain of these dynamics was one the parameter estimates converged to their true values.

The next effort to estimate the parameters was to continually solve the set of simultaneous equations that resulted each time a new set of measurements became available and average with the previous results or run through a first order filter. The resulting estimates were <u>very</u> poor. The noise biased the estimates and sometimes the resulting equations to be solved were poorly conditioned. Therefore this approach was abandoned.

Next, a hybrid technique was attempted. The idea was to combine Least Squares with a Kalman filter. The Least Squares estimation of the parameters would be used to determine the linear system parameters to use in the Kalman filter for the outputs. Then these filtered outputs would in turn be used to update the Least Squares estimation of the parameters. This technique converged to the wrong solution.

After attempting the hybrid solution it was decided to use a simpler process model than the 8 state AH-64 stability model to investigate the performance of subsequent P.I.D. algorithms. For initial work it was decided to use a first order difference equation with one input and zero mean, Gaussian, white process noise as follows :

$$X_{+} = A X + B U + W.$$

Where X is the state, U is the measured control input, W is the noise term, and A and B are the scalar parameters to be determined. The output equation is of the form :

$$Y = X + V.$$

Where Y is the measured output and V is zero mean, Gaussian, white and uncorrelated with W.

The first technique attempted using the above mentioned simplified model was the Extended Kalman filter. This method simultaneously predicts the state and parameters. The filter is formulated by first augmenting the state vector by appending the parameters to be estimated to the state vector. Next the resulting model is linearized about a trajectory, usually the currently estimated state. The standard state and covariance propogation equations are then used between measurements and the same update equations are used for the measurements as for the linear case since the measured output is linearly related to the state. In this formulation two approximations were used for the covariance propogation one assumed the F matrix to be constant over the interval and another used a numerical integration. An iteration over the nonlinear dynamics was used in hopes of getting better results. Despite the different techniques used they all yielded results that were inferior to the Least Squares Identification of the parameters.

The last technique tried was that of statistically linearized state and covariance propogation equations. Following are the equations for the state and covariance propogation using the notation of reference 1 from chapter 6.

E(Xdot) = E(f(X(t),t))

Pdot = E(f*X'+X*f') + E(f)*E(X') + E(X)*E(f')

The expected values were calculated assuming that the probability density function stayed approximately Gaussian. The performance of the resulting filter was found to be inferior to the Least Squares Identification. The derivation of the filter used is attached.

Following is a list of the references used for the above mentioned work :

1.* Gelb, Arthur, Applied Optimal Estimation, The M.I.T. Press, Cambridge, Mass., 1974.

2.* Bozic, S.M., Digital and Kalman Filtering, John Wiley and Sons, New York, 1979.

3.* Sage, A.P. and Melsa, J.L., Estimation Theory with Applications to Communication and Control, Krieger, New York, 1971.

4.* Brigham, E.O., The Fast Fourier Transform, Prentice-Hall Inc., Englewood Cliffs, N.J., 1974.

5. Bracewell, Ronald N., The Fourier Transform and its Applications, 2nd Ed., McGraw-Hill Book Co., New York, 1978.

6.* Hoskins, R.F., Generalised Functions, John Wiley and Sons, New York, 1979.

7. Bramwell, A.R.S., Helicopter Dynamics, John Wiley and Sons, New York, 1976.

8. Sage, A.P. and Melsa, J.L., An Introduction to Probability and Stochastic Processes, Prentice-Hall Inc., Englewood Cliffs, N.J., 1973.

9.* Sage, A.P. and White, C.C., Optimum Systems Control, 2nd Ed. Prentice-Hall Inc., Englewood Cliffs, N.J., 1977.

10.* Sage, A.P. and Melsa, J.L., System Identification, Academic Press, New York, 1971.

11.* Eykhoff, Pieter, System Identification : Parameter and State Estimation, John Wiley and Sons, New York, 1974.

* Denotes those books available through the HHI library.

Estimated Second Year Budget

	McDonnell Douglas	Ga. Tech
Salaries and Wages		
Co-Principal Investigators		
D.P. Schrage (3% time)	$ 2,520	
B.H. Tongue (3% time)	1,500	
Total Salaries and Wages	3,500	$ 520
Retirement Benefits		
21% of Direct Salaries Wages	735	109
Travel		
Two trips, one to MDHC and one to a technical meeting to present results	2,493	
Computer Cost		
Total Direct Charges	$ 6,728	$ 629
Overhead		
63.5% of Direct Charges	4,272	399
Total Research Cost	$11,000	$1,028
MDHC Graduate Co-op Research Fellowship (Includes Tuition & Fees)		
P. Fitzsimons	14,000	____
TOTAL COST	$25,000	$1,028

Encl 2

IRAD Status Report

Project No. ____________________

Date November 10, 1986

Project Name ____________________

Reporting Period July 1 - Sept. 30, 1986

Responsible Engr ____________________

Percent Spent ____________________

MJO ____________________

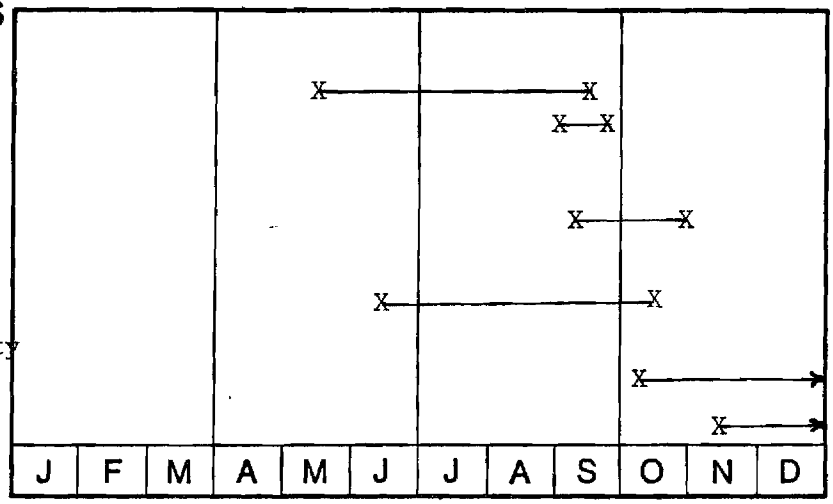
Percent Accomplished ____________________

SUMMARY OF PROGRAM OBJECTIVES

Design of a Helicopter Automatic Flight Control System Using Adaptive Control

SCHEDULE OF TASKS/MILESTONES

- Model AH-64 using ARMCOP
- Determine Linearized Models of AH-64
- Compensate Linear Models to Meet Mil-Spe 8501B
- Determine MRAC Design for Nonlinear Systems
- Determine State Space Model for Stability Analysis
- Implement MRAC and STR Designs on ARMCOP



MANHOURS

J F M A M J J A S O N D

DOLLARS

J F M A M J J A S O N D

FORM NO. 10340

Hughes Helicopters, Inc.
A Subsidiary of McDonnell Douglas

SUMMARY OF PROGRAM ACCOMPLISHMENTS/PROBLEMS FOR REPORTING PERIOD

Following is a brief report of the progress that has been made on the IRAD project entitled "Design of a Helicopter Automatic Flight Control System Using Adaptive Control". Modelling of the AH-64 using ARMCOP was completed in September. During the months of September and October two linearized models of the AH-64 were determined using ARMCOP one for hover and another for 130 knots. The resulting models were compensated using eigenstructure assignment to decouple the longitudinal and lateral axes and to yield desireable transients. The compensated models meet the requirements specified in the proposed Mil-Spec 8501b as given in "Proposed Airworthiness Design Standard: Handling Qualities Requirements for Military Rotorcraft" a 1985 report by Systems Technology Inc.

Additionally, an extension of the Adaptive Model Following Control scheme as specified by Landau in his book ADAPTIVE CONTROL has been determined that will work with certain nonlinear systems.

PROJECTED ACCOMPLISHMENTS/PROBLEMS FOR NEXT REPORTING PERIOD

- Develop state-space model of helicopter for stability analysis
- Pursue theoretical developments of MRAC and STR as applied to control of nonlinear systems
- Implement MRAC and STR in ARMCOP simulation of AH-64 and evaluate performance of the two different control schemes

IRAD Status Report

Project No. ______________________

Project Name ______________________

Responsible Engr ______________________

MJO ______________________

Date July 15, 1986

Reporting Period January 1 - June 30, 1986

Percent Spent ______________________

Percent Accomplished ______________________

SUMMARY OF PROGRAM OBJECTIVES

Design of a Helicopter Automatic Flight Control System Using Adaptive Control

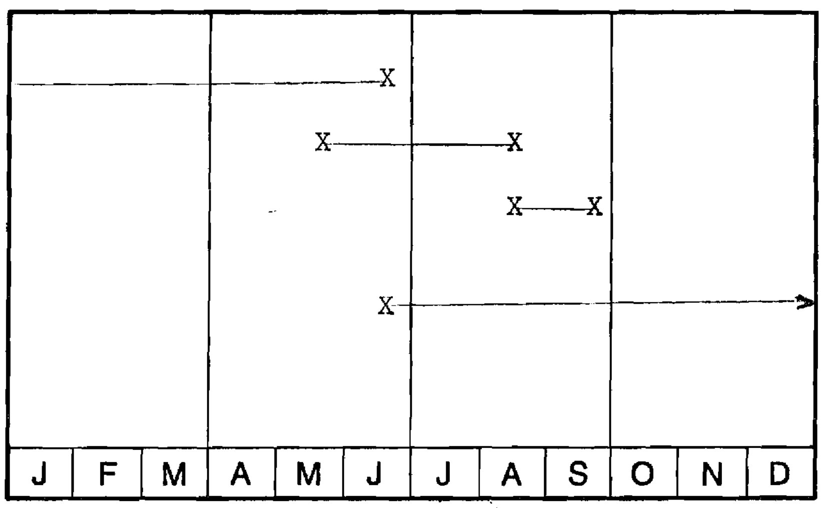
SCHEDULE OF TASKS/MILESTONES

Present paper on P.I.D.

Model AH-64 on ARMCOP

Determine satisfactory reference models

Determine MRAC and STR designs



MANHOURS

J F M A M J J A S O N D

DOLLARS

J F M A M J J A S O N D

FORM NO. 10340

Hughes Helicopters, Inc.
A Subsidiary of McDonnell Douglas

SUMMARY OF PROGRAM ACCOMPLISHMENTS/PROBLEMS FOR REPORTING PERIOD

Various parameter identification techniques were developed and applied to simplified dynamic models, first a one degree of freedom model and then a four degree of freedom model representing a light helicopter.

During this period a paper on the parameter identification techniques developed was written and presented at the 42nd annual AHS Forum. This work covered the period from January 1, to June 30, 1986.

PROJECTED ACCOMPLISHMENTS/PROBLEMS FOR NEXT REPORTING PERIOD

The remainder of the summer is being spent modeling the AH-64 helicopter using the NASA/Army program ARMCOP. Two linearized models of the Apache, one at hover and one at cruise will be determined. These will be augmented using standard linear system design procedures to meet the new Army Flying Quality Specification and the resulting system will be used as the reference model in subsequent design work. These reference models should be determined by the end of September 1986. Following will be an effort to incorporate two different control designs into ARMCOP. One will use the Model Reference Adaptive Control (MRAC) approach while the other will use the Self Tuning Regulator (STR) design approach.

See Attachment

The math model to be used in the research is that of the AH-64 as it is modeled in ARMCOP.

Control System Design

1) Determine two unaugmented linear models of the AH-64. One for hover and another for cruise.

2) Augment the above determined linear models such that the augmented system satisfies performance requirements.

3) Using MRAC and the augmented linear model determined in 2 above as the reference model design a control system.

4) Using STR and the augmented linear model determined in 2 above as the reference model design a control system.

5) Using ARMCOP evaluate the performance of the control systems in 3 and 4 and make recommendations and conclusions.

Research Proposal
for
Third Year

Submitted to

McDonnell Douglas Helicopter Company

DESIGN OF A HELICOPTER AUTOMATIC FLIGHT CONTROL SYSTEM

January 27, 1987

D. P. Schrage, Professor
School of Aerospace Engineering
Principal Investigator

W. M. Sangster, Dean
College of Engineering

R. B. Gray, Acting Director
School of Aerospace Engineering

J. L. Goldbaugh
Contracting Officer

PROPOSAL UPDATE FOR THIRD YEAR
"DESIGN OF A HELICOPTER AUTOMATIC FLIGHT CONTROL SYSTEM"

1. INTRODUCTION

The original subject proposal was a three-year effort to design a helicopter automatic flight control system based on the application of parameter identification techniques and the use of optimal control theory to develop an adaptive controller. This work is continuing and the purpose of this update is to review the status of the research, project results at the end of the third year, and update the third-year budget based on changes in Georgia Tech's retirement and overhead rates.

2. STATUS OF RESEARCH

This project involves a graduate co-op student, Mr. Philip FitzSimons, who spent most of the first year at the sponsor's facility, McDonnell Douglas Helicopter Company in Mesa, Arizona. At Georgia Tech this is a joint project between the Schools of Aerospace and Mechanical Engineering. The tasks in the original three-year proposal is included as Attachment 1. While these tasks have been modified slightly during the first two years the final objective to determine the best adaptive control strategy in the design of a helicopter automatic flight control system is still on track.

The emphasis during the first year was to investigate parameter identification techniques that could be used in formulating an adaptive control strategy. Various parameter identification techniques were developed and applied to simplified dynamic models, first a one degree of freedom model and then a four degree of freedom model representing a light helicopter. During this period a paper on the parameter identification techniques developed was written and presented at the 42nd Annual AHS Forum. A copy of this paper is Attachment 2.

During this, the second year, the research has involved developing nonlinear and linear mathematical models of a representative helicopter, investigating and evaluating evolving helicopter flying qualities criteria, and formulating an adaptive control strategy. Based on discussions with the sponsor the AH-64 "Apache" helicopter was selected as the representative helicopter. By the end of the third quarter a nonlinear model of the AH-64 was developed using the ARMCOP simulation model. During the months of September and October two linearized models of the AH-64 were determined using ARMCOP, one for hover and another for 130 knots. The resulting models were compensated using eigenstructure assignment to decouple the longitudinal and lateral axes and to yield desirable transients. The compensated models meet the requirements specified in the proposed Mil-Spec 8501B, Handling Qualities Requirements for Military Rotorcraft." Additionally, an extension of the adaptive model following control scheme as specified by Landaw in his book ADAPTIVE CONTROL has been determined that will work with certain nonlinear systems. Current work includes the development of a state-space analytical model of the helicopter that can be used for stability analysis and be consistent with the ARMCOP simulation. An on-site visit and briefing of the research efforts were provided at the sponsor's facility in Mesa, Arizona, during September 1986. A paper on the second year's effort will be proposed for the Thirteenth European Rotorcraft Forum.

3. THIRD YEAR EFFORT

The efforts during the third year will be aimed at determining the best adaptive control strategy for designing an AH-64 automatic flight control system. This will be accomplished by pursuing theoretical developments of Model Reference Adaptive Control (MRAC) and Self Tuning Regulator (STR) as applied to control of nonlinear systems. This will be followed by implementation of MRAC and STR in the ARMCOP simulation of the AH-64 and an evaluation of the performance of the two different control schemes. A paper and final report will then be published documenting the results. The third-year budget is included as Attachment 3.

Attachment
schrage.081/rm

Tasks

Year 1

(a). Become proficient with Flyrt and Triplm.

(b). Develop a six degree-of-freedom reduced order model.

(c). Identify system control parameters by means of:

(i) Kalman Filtering
(ii) Recursion
(iii) Maximum Likelihood
(iv) Other

(d). Apply results of part (c) to:

(i) Hover
(ii) Cruise at 120 knots for predetermined inputs

(e). Publish Paper.

Year 2

(a). Combine all available handling qualities data into a statistically presentable form.

(b). Use part (a) to help generate a mathematical model that yields the "optimal" handling qualities.

(c). Publish Paper.

Year 3

(a). Determine the penalty matrices required to allow the actual system to track the optimal model.

(b). Determine how much of the optimal regulation problem can be solved on-line.

(c). Determine the best adaptive control strategy to connect the steady state flight regimes to allow acceptable control throughout the flight envelope.

(d). Publish Paper.

ATTACHMENT 2

NON-ITERATIVE PARAMETER IDENTIFICATION TECHNIQUES

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Abstract

Central to virtually all aspects of helicopter design and evaluation is an appropriate mathematical model. The model structure is chosen to adequately represent the physical behavior of the phenomena under study. These models are usually parametric in nature and so the analyst is faced with the task of determining appropriate values to be assigned to the relevant parameters. This is often done by observing input/output measurements and choosing the parameters that in some sense best fit the model to the observations. This procedure is known as parameter identification. In the following paper the model structure is restricted to being linear and time-invariant. Descriptions of three different non-iterative techniques that can be used to determine parameter estimates are given in this paper. The techniques are Deterministic (Recursive) Least Squares (DLS), the Extended Kalman Filter (EKF), and the Statistically Linearized Filter (SLF). The methods are then used to identify the parameters of two different systems. The first is a simple one state, two parameter system. The second is a four state, twenty four parameter system taken from a linearized longitudinal model of an Advanced Light Helicopter (ALH) in forward flight.

Introduction

When working with complex systems such as the helicopter it is often necessary to use simplified models of the phenomena being studied. Often these simplified models lead to linear time-invariant systems. One particular example of this is the use of stability derivatives for handling qualities models.

If it is possible to determine the stability derivates on-line then it may be feasible to design an adaptive control system using the Self-Tuning Regulator (STR) concept.[1] This necessitates the need for non-iterative parameter identification algorithms in order to meet time constraints. The following pages present descriptions of used for parameter identification. Computer results obtained from the identification of two different systems are presented. These results are the basis for recommendations about the different algorithm's relative benefits and shortcomings.

Algorithm Development

Before discussing the parameter identification schemes it will prove helpful to introduce the basic model and the assumptions used throughout this paper. The form of the model is:

Process

$$x(i+1) = Ax(i) + Bu(i) + w(i) \qquad (1a)$$

Measurement

$$y(i) = Cx(i) + v(i). \qquad (1b)$$

C is assumed to be known. W(i) and v(i) are independent, white, Gaussian noise sequences with covariance matrices Wvar and Vvar, respectively. W(i) and v(i) are also independent of u(i) and x(0) for all i. The input signal, u(i) used to drive the system to be identified is a zero mean, white, Gaussian sequence. Though this is not physically realizable it is a convenient idealization and ensures that the system is persistently excited. The system used to generate the output signals has the same structure as the model.

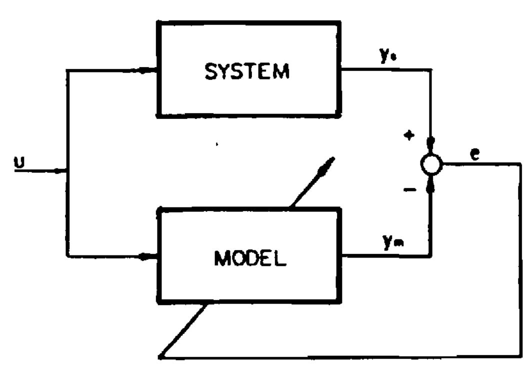

FIGURE 1

The objective of the parameter identification is to determine the elements of A and B. The error measure used to drive the algorithms is the difference between the observed output and the output predicted by the model, commonly referred to as the output prediction error (see Fig. 1). The parameter estimates at each time step are determined by minimizing a positive definite quadratic function of the past and present errors. This leads to Least Squares parameter estimates. For the deterministic case, Least Squares Estimates are easily computed (in principle). However, for the stochastic case the Least Squares Estimates are the conditional expected values of the parameters given the observed measurements. These conditional expected values are usually difficult (or impossible) to calculate. Therefore suboptimum solutions are determined by restricting the form of the estimator.

Deterministic Least Squares

The first algorithm to be discussed is the Deterministic Least Squares technique. This is the simplest of the three algorithms. It is also the easiest to implement. The statistical properties of the signals are neglected. The quadratic function of the error mentioned above is minimized deterministically. The parameters identified are those that best fit the model to the observed input/output data. In addition to the previously mentioned assumptions it is assumed that C is square and invertible.

The following definitions are used assuming measurements have been taken through time step i:

$$V = \begin{bmatrix} y(0), y(1), \ldots, y(i-1) \\ u(0), u(1), \ldots, u(i-1) \end{bmatrix}$$

$$Y = [y(1), y(2), \ldots, y(i)].$$

The output error is expressed as:

$$E = Y - C[\hat{A}C^{-1}|\hat{B}]V. \qquad (2)$$

The function to be minimized by the choice of A and B is:

$$J = Tr(EWE^T). \qquad (3)$$

W is a positive definite weighting matrix. For the purposes of this paper W is the identity matrix or it is diagonal and is constructed such that the weighting decreases exponentially with the age of the associated error term. This second case allows the parameter estimates to track slowly varying system parameters.

The solution of the above optimization problem is:

$$[\hat{A}C^{-1}|\hat{B}] = C^{-1}YWV^T(VWV^T)^{-T} \qquad (4)$$

Using the matrix inversion lemma and rearranging terms allows the above solution to be cast in a recursive form so that new parameter estimates may be computed as new measurements become available. For a description of this recursive solution the reader is referred to Franklin and Powell.[2]

The next two algorithms to be discussed take the statistical characteristics of the signals into consideration. The expected value of the quadratic error criteria mentioned above is minimized when the conditional expected values of the parameters are chosen as the parameter estimates. However, it is rarely possible to calculate these conditional expectations. Gradient search techniques are sometimes used to find the maximum value of the conditional probability density function (Maximum Likelihood) numerically. Unfortunately this does not necessarily correspond to the Least Squares Estimate and the solution technique is iterative. Therefore it will not be discussed.

It is apparent that a suboptimal scheme will be necessary if the process is to be non-iterative. Two algorithms are discussed below. They both draw on results associated with the Kalman Filter. It is known that, given a finite-dimensional linear model such as the one above with known parameters, that the Least Squares Estimates of the states are given by the Kalman Filter. It is interesting to note that the optimal estimates are linear functions of the observations. This is very convenient for numerical manipulations since results from numerical linear algebra can be used.

The Extended Kalman Filter

The first technique that is to be discussed in the stochastic framework is the Extended Kalman Filter. The unknown parameters are appended to the state vector x to form a new augmented state vector z. The signal model becomes:

$$z(i+1) = f(z(i), u(i), w(i)) \quad (5a)$$

$$y(i) = Hx(i) + v(i) \quad (5b)$$

where $H = [C|0]$.

The implementation of the EKF is as follows. The initial state $z(0)$ is assumed to have a Gaussian distribution with mean $\hat{z}(0/0)$ and covariance $P(0/0)$. Here the notation $\hat{z}(i/j)$ denotes the conditional expected value of $z(i)$ given measurements through time step j. The filter has two stages that take place recursively. The first is the time update. The time update propogates the mean and covariance of z. It is during this step that the approximation for the nonlinear dynamics of (Eq. 5a) is made. The mean and covariance are updated as follows:

$$\hat{z}(i+1/i) = f(\hat{z}(i/i), u(i), 0) \quad (6)$$

$$P(i+1/i) = FP(i/i)F^T + Wvar^* \quad (7)$$

where

$$F = \frac{\partial f}{\partial z}\Big|_{z=\hat{z}(i/i)} \text{and } Wvar^* = \begin{bmatrix} Wvar & 0 \\ 0 & 0 \end{bmatrix}$$

The random vector $\hat{z}(i+1/i)$ is now specified by the above mean and covariance. The measurement update follows. The measurement update uses the measurement $y(i+1)$ to specify the random vector $\hat{z}(i+1/i+1)$. Hence the new estimate of $z(i+1)$ becomes the mean $\hat{z}(i+1/i+1)$. The measurement updates are:

$$\hat{z}(i+1)/i+1) = \hat{z}(i+1/i) +$$

$$K(i+1)(y(i+1) - H\hat{z}(i+1/i)) \quad (8)$$

$$P(i+1/i+1) = P(i+1/i) - P(i+1/i)H^T$$

$$(HP(i+1/i)H^T + Vvar)^{-1} HP(i+1/i) \quad (9)$$

$$K(i+1) = P(i+1/i+1)H^T Vvar. \quad (10)$$

Following the measurement update the time index i is incremented and the above process is repeated as new measurements become available.

It is apparent that now the covariance and Kalman gain are random matrices since they depend on the augmented state estimate. It is therefore no longer possible to precompute the Kalman gain as is possible with the standard Kalman filter. Therefore this technique is computationally more demanding than the standard Kalman Filter. It also requires more computations per time step than the DLS algorithm.

Caution must be exercised when using this filter due to the possibility of divergence. For a discussion of the convergence characteristics of the EKF the reader is referred to [Ljung].[3]

Before proceeding to the Statistically Linearized Filter a brief digression on its motivation is given. Since the construction of an estimator that is optimal in the Least Squares sense is often not possible, optimal estimators with a restricted structure are sought. A common restriction is that the estimate be a linear function of the observations. Given the structure and that the noise and initial condition are jointly Gaussian the optimal Linear Least Squares Estimate can in principle be calculated. However, as more data becomes available it is necessary to determine high order moments of the original distribution. The computation time required to calculate these moments increases with each additional measurement. Therefore an estimator of this type is not practical. However, if the distribution of the augmented state is assumed to remain Gaussian (ie. is characterized by its first and second moments) a recursive estimation algorithm can be constructed.

<u>The Statistically Linearized Filter</u>

The resulting algorithm is the Statistically Linearized Filter. The only difference between this filter and the EKF is in the time update. Instead of linearizing the dynamics about the current estimate of z and then calculating the updated mean and covariance, the updated mean and covariance are calculated directly from the nonlinear relationship given in (Eq. 5a). The time updates are:

$$\hat{z}(i+1/i) = E\{f(i)\} \quad (11)$$

$$P(i+1/i) = E\{(f(i)$$

$$- \hat{z}(i+1/i))(f(i)$$

$$- \hat{z}(i+1/i))^T\} \quad (12)$$

where $f(i) = f(z(i), u(i), w(i))$ and $E\{\ \}$ is the expectation operator. The measurement update equations are the same as those given in Eqs. 8-10. Again, it is necessary that higher order moments of a Gaussian distribution be calculated. However, the same moments are calculated at each time step. Therefore the recursion is:

(1) update the mean and covariance using the nonlinear dynamic equation

(2) take measurement y(i+1)

(3) calculate the new estimates of the mean and covariance

(4) repeat starting at step 1.

Results

The linear analysis package CTRL-C is used to generate the following results. Before presenting them the purpose of the simulations is discussed. Since parameter identification for a system of the type discussed in this paper is basically a nonlinear estimation problem it is difficult to make general statements about the characteristics of the estimators without making rather restrictive assumptions. Observations made from simulations can be used to determine which estimation routines offer promise and should be further investigated. Once this is established a more thorough investigation of the statistical properties of the estimators can be justified.

Restricting the models to have the structure and satisfy the assumptions given previously results in the estimators generally giving biased estimates. The question of concern is whether or not these estimates are consistent (converge to the actual system parameters). This question will only be considered by way of the simulation results in this paper. The interested reader is referred to the literature for a formal treatment [1,3,6,8].

As mentioned previously two systems are used to evaluate the identification algorithms. The first system considered is a one state, two parameter system. For this system three test cases consisting of fifty different simulations each are run. The parameter estimates from each simulation are averaged for each time and the resulting Monte Carlo results are given in plots 1-3. For the second system two test cases consisting of ten simulations each are run. Due to the computational requirements of the SLF it is used with only one simulation per test case. Since the number of parameters to be determined for this system is large the matrix 2-norm of the matrices formed by the difference between the actual and identified A and B matrices is used to indicate how close the identified matrices are to the actual system matrices. This norm relates to the Frobenius norm as follows:

$$\|\cdot\|_F \leq \sqrt{n}\ \|\cdot\|_2$$

(n = rank of argument)

where the Frobenius norm is defined as[4]:

$$\|A\|_F = \left[\sum_{i,j} |a_{ij}|^2\right]^{1/2}$$

System 1

The initial estimates of the states and parameters for each of the identification routines used is zero for all of the simulations. The initial covariance of the augmented state vector is the identity matrix. For the DLS case it is the 2 x 2 identity matrix. As mentioned previously the control input u used to excite the system is a white, Gaussian sequence. It is given a covariance of unity in the following simulations. The actual system parameters are:

$$A = 1 \quad : \quad B = 1.$$

The first case has noise covariances:

Vvar = 0.25 : Wvar = 0.0.

In plots 1a and 1b it can be seen that the EKF and the SLF converge the fastest to the system parameters. The SLF has the smoothest transient behavior. The DLS estimate has still not converged after one hundred time steps.

The second case has noise covariances:

Vvar = 0.01 : Wvar = 0.25.

The results from this case are given in plots 2a and 2b. It is very difficult to tell the difference between the estimates of the Extended Kalman Filter and the Statistically Linearized Filter after a short time. All of the estimates appear to converge to the actual parameters.

The third case has noise covariances:

Vvar = 0.25 : Wvar = 0.25.

These results are displayed in plots 3a and 3b. In this case all of the estimates appear to converge slower than in the previous cases. However, this is to be expected due to the inclusion of two large noise terms instead of just one. Again it is observed that the estimates of the EKF and the SLF are indistinguishable after a short time period.

For this simple system all of the estimators work reasonably well. However, a persistent bias appears to be present in the estimate made by the DLS algorithm when the measurement noise covariance is large. The computing requirement for all three of the algorithms is modest for this system.

System 2

The second system to be considered is a linearized longitudinal model of an Advanced Light Helicopter (ALH) in forward flight (sea level, 120 KMPH).[5] The system parameters are:

$$A=\begin{bmatrix} 0.99583 & 0.00892 & -0.20386 & -0.97699 \\ 0.00474 & 0.90231 & 3.02034 & -0.06579 \\ 0.00052 & -0.00041 & 0.91685 & -0.00024 \\ 0.00003 & -0.00002 & 0.09577 & 0.99999 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.85532 & 1.20743 \\ -1.33815 & -12.77270 \\ 0.99958 & 0.84003 \\ 0.05068 & 0.04254 \end{bmatrix}$$

where the system has been discretized to one tenth second intervals assuming a zero order hold on the input. The states in descending order are the longitudinal airspeed u (m/sec), the vertical airspeed w (m/sec), the pitch rate q (rad/sec) and the pitch angle (rad). The controls in descending order are the longitudinal cyclic and collective blade pitch at the root (rad). It is assumed that the states are made available by noisy measurements (i.e. C is the identity matrix). The process noise w(i) is identically zero. The initial parameter and state estimates are zero in all of the simulations. The initial covariance matrix for the EKF and the SLF is chosen to be diagonal with initial state variances equal to unity and initial parameter variances equal to the absolute value of the actual parameter when its magnitude is less than one or the square of the actual parameter when its magnitude is greater than one. The initial covariance used in the DLS algorithm is diagonal with each term on the diagonal equal to one hundred. The choice of the control and measurement covariances below is made by selecting a value for the term considered that corresponds to a 2 sigma deviation from the mean. The covariance of the excitation input used in the following simulations is:

$$Uvar = \begin{bmatrix} 2.5E-3 & 0.0 \\ 0.0 & 2.5E-3 \end{bmatrix}$$

In the first case the measurement noise covariance is:

$$Vvar = \begin{bmatrix} 4.823E-1 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.929E-2 & 0.0 & 0.0 \\ 0.0 & 0.0 & 4.760E-4 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.904E-3 \end{bmatrix}$$

This corresponds to relatively noisy measurements. The results from this test case are given in plots 4a and 4b. The SLF appears to do a superior job identifying the system over the EKF and the DLS. However, this is at the expense of a significant computational requirement and considers only one simulation for the SLF. It is reasonable to assume that for stationary statistics and the same initial conditions that the convergence characteristics of the SLF will be similar for the other simulation runs. None of the algorithms appear to properly identify the B matrix.

The measurement noise covariance for the second test case is:

$$Vvar = \begin{bmatrix} 1.929E-2 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.929E-4 & 0.0 & 0.0 \\ 0.0 & 0.0 & 4.760E-6 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.904E-5 \end{bmatrix}$$

The results from this test case are given in plots 5a and 5b. All of the algorithms appear to converge for the estimation of the A matrix. The B matrix appears to still not be properly identified. As in the previous case the SLF estimate is the closest to the actual parameters.

Conclusions and Recommendations

The computational requirements of the above algorithms are in ascending order the DLS, the EKF and the SLF. From the above results it is clear that the SLF gives superior parameter estimates. However, it has been determined that the SLF can not be implemented in real-time unless the speed of flight computers increases significantly over those currently available. Though not practical for real-time parameter identification the SLF warrants further study as an off-line identification technique. It may compare favorably with some of the iterative off-line identification algorithms.

Realizing that for a practical controller a larger model and hence more parameters will need to be identified than in the above simple case the DLS and the EKF or similar techniques seem to be the only practical solutions to the parameter identification problem. Modified versions of the DLS and the EKF that seem to overcome some of the bias and divergence problems associated with these algorithms are given in the literature [1,3,6,8].

Acknowledgement

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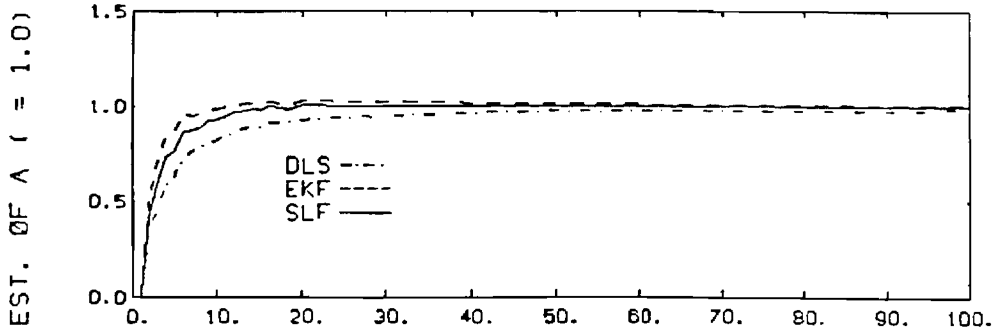

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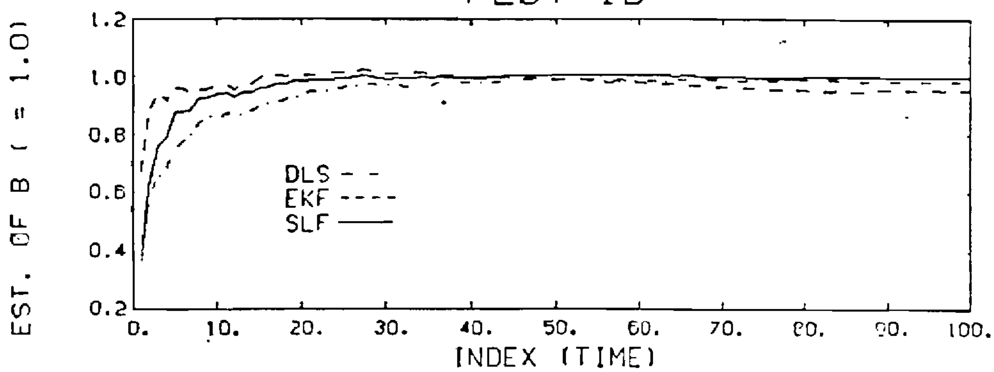

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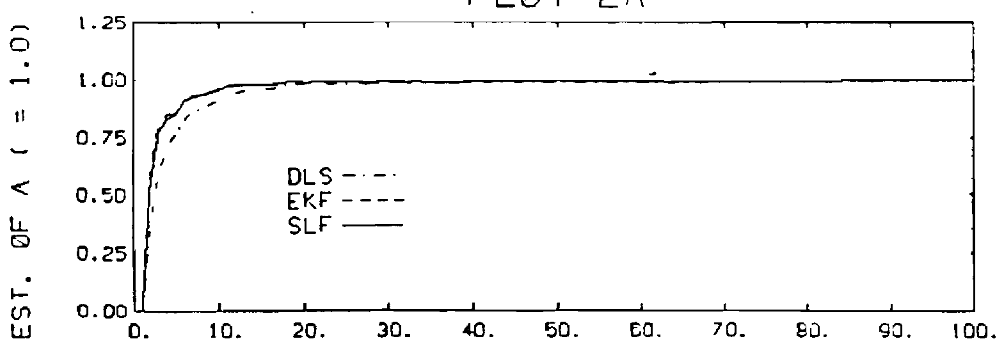

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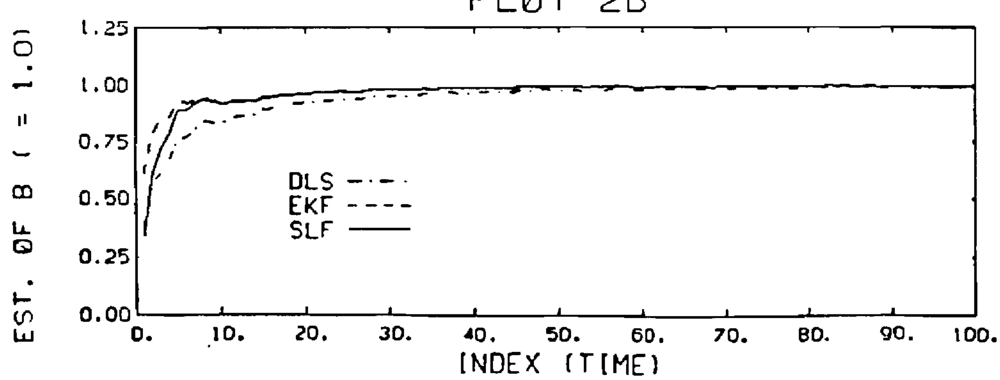

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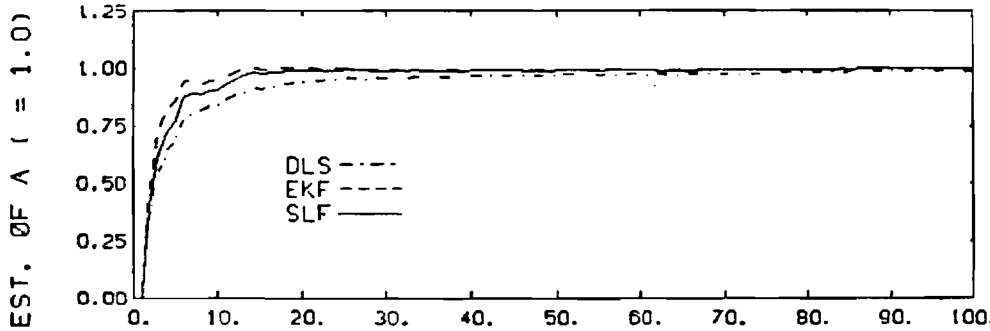

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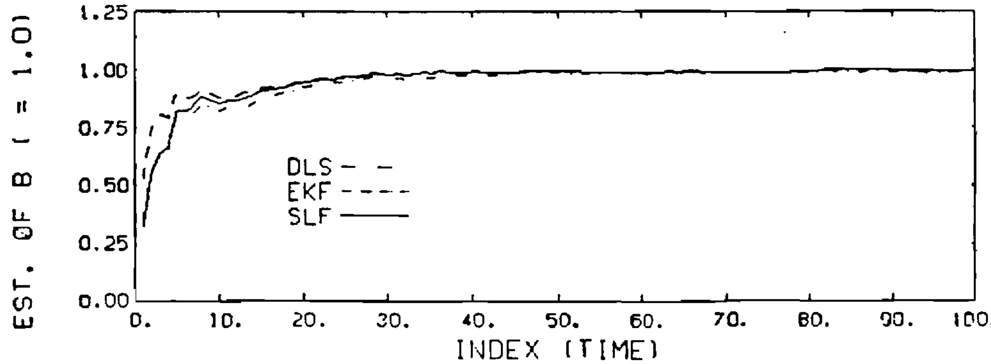

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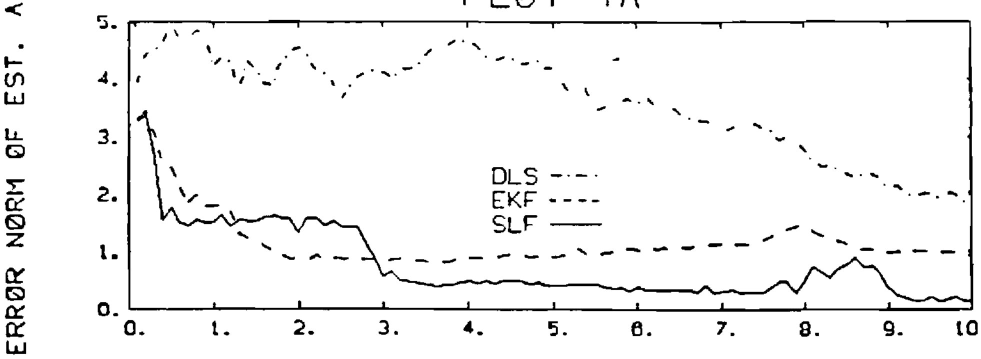

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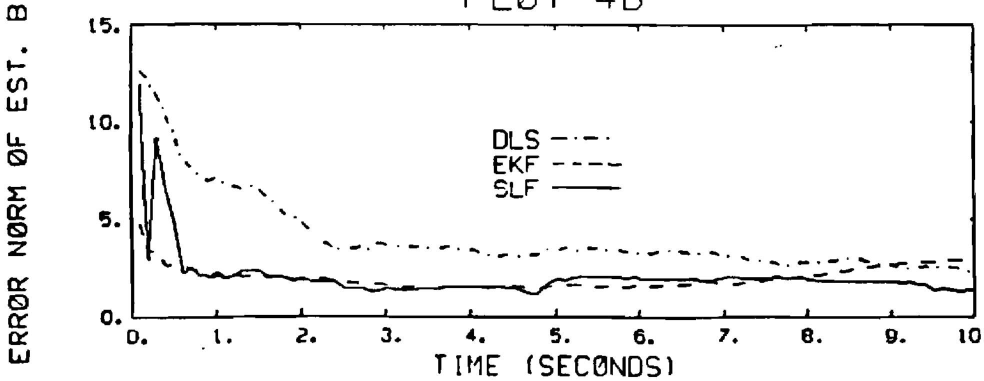

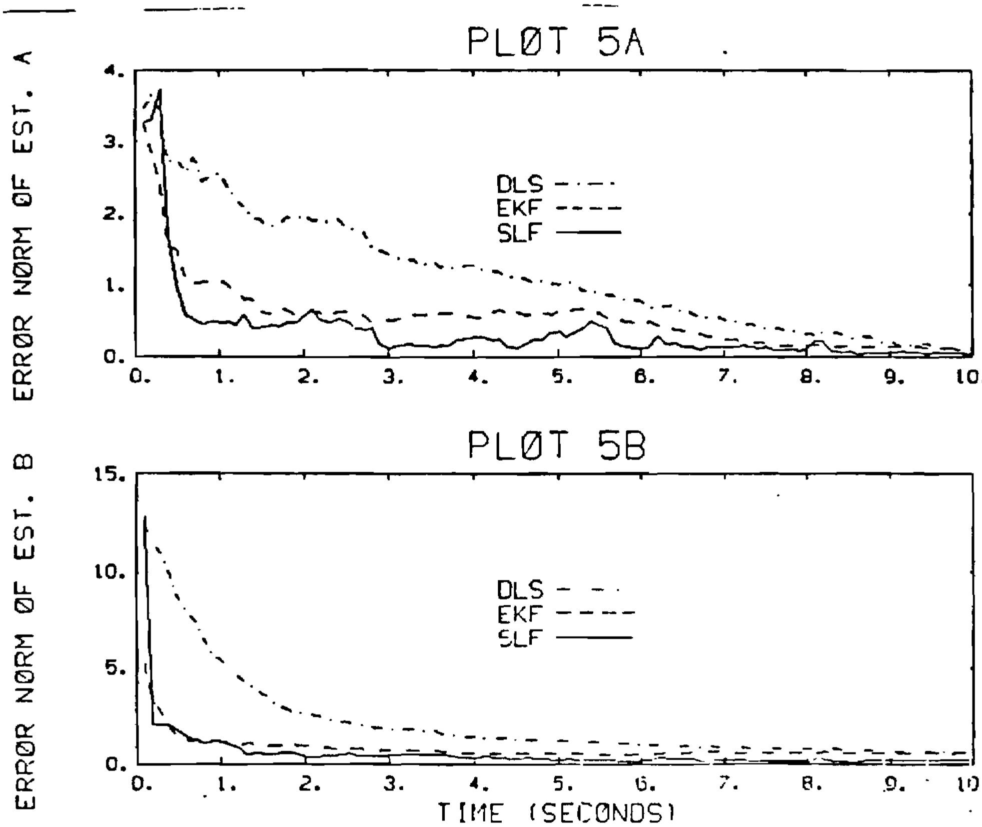
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UMMARY OF PROGRAM OBJECTIVES

Design of a Helicopter Automatic Flight Control System Using Adaptive Control

CHEDULE OF TASKS/MILESTONES

lodel AH-64 using ARMCOP

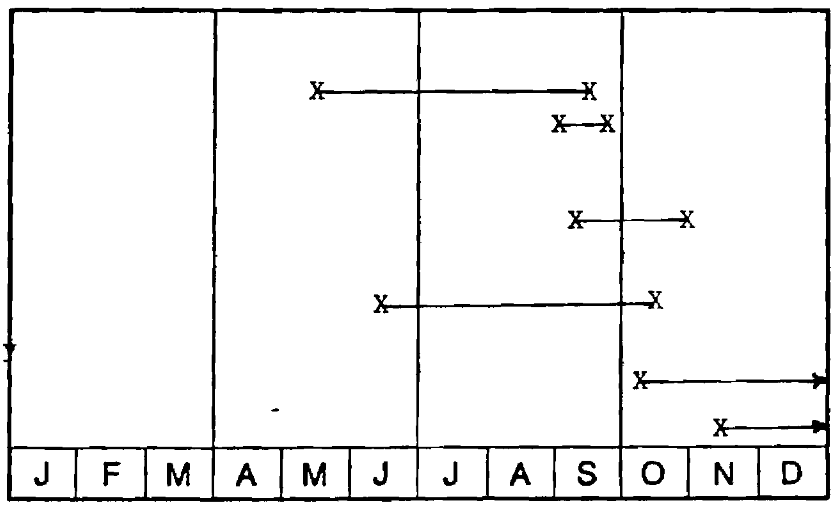
etermine Linearized Models of AH-64

ompensate Linear Models to Meet Mil-Spe 8501B

etermine MRAC Design for Nonlinear Systems

etermine State Space Model for Stability Analysis

nplement MRAC and STR Designs on ARMCOP



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Hughes Helicopters, Inc.

›MMARY OF PROGRAM ACCOMPLISHMENTS/PROBLEMS FOR ›PORTING PERIOD

Following is a brief report of the progress that has been made on the IRAD project entitled "Design of a Helicopter Automatic Flight Control System Using Adaptive Control". Modelling of the AH-64 using ARMCOP was completed in September. During the months of September and October two linearized models of the AH-64 were determined using ARMCOP one for hover and another for 130 knots. The resulting models were compensated using eigenstructure assignment to decouple the longitudinal and lateral axes and to yield desireable transients. The compensated models meet the requirements specified in the proposed Mil-Spec 8501b as given in "Proposed Airworthiness Design Standard: Handling Qualities Requirements for Military Rotorcraft" a 1985 report by Systems Technology Inc.

Additionally, an extension of the Adaptive Model Following Control scheme as specified by Landau in his book ADAPTIVE CONTROL has been determined that will work with certain nonlinear systems.

›ROJECTED ACCOMPLISHMENTS/PROBLEMS FOR NEXT REPORTING PERIOD

- Develop state-space model of helicopter for stability analysis
- Pursue theoretical developments of MRAC and STR as applied to control of nonlinear systems
- Implement MRAC and STR in ARMCOP simulation of AH-64 and evaluate performance of the two different control schemes