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L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

MVPACK: A COMPUTER-AIDED DESIGN TOOL FOR MULTIVARIABLE CONTROL SYSTEMS

MVPACK: Un outil de conception assisté par ordinateur pour système de commande multivariables

S. MENSAH and G. FRKETICH

Presented at the 1984 Canadian Conference on Industrial Computer Systems,
Ottawa, 1984 May 22-24

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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Résumé

La conception et l'analyse de contrôleurs à rendement élévé pour des systèmes complexes, demande une collection de programmes puissants et interactifs pour ordinateur.

MVPACK, un paquet ouvert de programmes pour les systèmes de conception assisté par ordinateur, a été développé au département de contrôle des reacteurs des laboratoires nucléaires de Chalk River. Le paquet de programmes est complètement interactif et y inclus une bibliothèque compréhensive de mathématiques, des plus modernes, supportant le développement d'algorithmes de commande complexes et multivariables.

Codé en RATFOR, avec un minimum de changements, MVPACK est portatif. Il fonctionne avec une structure flexible de données, ce qui utilise efficacement les ressources de mini-ordinateur et pourvoit une charpente standard pour la création de programmes. L'existence d'un mécanisme de secours rehausse la simplicité de l'utilisation du paquet.

Ce papier donne une brève revue de l'ensemble du paquet. Il revoit les spécifications utilisées dans le planning et l'implantation du paquet et décrit brièvement la structure de la banque de données, des bibliothèques de soutien et de quelques desseins et modules d'analyse du MVPACK. Afin d'illustrer la capacité du paquet, plusieurs exemples sont donnés.

L'expérience avec MVPACK montre que ce paquet de programmes donne un environnement synergétique pour le planning de systèmes de commande et de règlements, et qu'il est un outil unique pour l'education des ingénieurs des systèmes de commande.

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ABSTRACT

The design and analysis of high-performance controllers for complex plants require a collection of interactive, powerful computer software.

MVPACK, an open-ended package for the computer-aided design of control systems, has been developed in the Reactor Control Branch of the Chalk River Nuclear Laboratories. The package is fully interactive and includes a comprehensive state-of-the-art mathematical library to support development of complex, multivariable, control algorithms.

Coded in RATFOR, MVPACK is portable with minimal changes. It operates with a flexible data structure which makes efficient use of minicomputer resources and provides a standard framework for program generation. The existence of a help mechanism enhances the simplicity of package utilization.

This paper provides a brief tutorial overview of the package. It reviews the specifications used in the design and implementation of the package and briefly describes the database structure, supporting libraries and some design and analysis modules of MVPACK. Several application examples to illustrate the capability of the package are given.

Experience with MVPACK shows that the package provides a synergistic environment for the design of control and regulation systems, and that it is a unique tool for training of control system engineers.

INTRODUCTION

Most complex plants in the chemical, process, and nuclear power industries are multivariable. They have several outputs that must be controlled and several inputs that may be adjusted. They also have strong dynamic interaction because each input may affect several outputs. The design and analysis of high-performance controllers for such plants require the use of rigorous multivariable techniques.

Analysis of multivariable systems is complex, and an extensive framework of mathematics is needed to develop the underlying theorems. The large number of matrix manipulations required makes extensive digital computer programs essential, both to perform arithmetic on real, complex, and polynomial matrices, and to execute the complex algorithms used in multivariable techniques. The wide acceptance of these techniques in industrial applications seems to require

- availability of tools that make all the mathematical complexity transparent to the control engineer, allowing him to concentrate on the design problem,

- analysts with the technical training to develop and implement the most promising techniques, and

- experimental or analytical demonstration of the performance of multivariable techniques on industrial problems.

It is now widely recognized that an integrated Computer-Aided-Design (CAD) package can be used to meet these requirements [1].

MVPACK, an open-ended package for the computer aided design of control systems, has been developed in the Reactor Control Branch of the Chalk River Nuclear Laboratories [2]. The package is fully interactive and includes a comprehensive state-of-the-art mathematical library to support development of complex, multivariable, control algorithms.

Coded in RATFOR, MVPACK is portable with minimal changes. It operates with a flexible data structure which makes efficient use of minicomputer resources and provides a standard framework for program generation. The existence of a help mechanism enhances the simplicity of package utilization.

This paper provides a brief tutorial overview of the package. It reviews the specifications used in the design and implementation of the package and briefly describes the database structure, supporting libraries and some design and analysis modules of MVPACK. Several application examples to illustrate the capability of the package are given.

SPECIFICATIONS OF MVPACK

MVPACK consists essentially of interaction methods, a mathematical library, database, and design or application programs. The package was designed and implemented to meet the following specifications.

Interactions, Expandability and Portability

The design process is not deterministic, so the designer must be able to influence the job as it progresses. At the beginning of his investigations, the designer simply may be unable to specify what he really wants because he lacks information on what he will have to pay, in engineering terms, for various aspects of desired final system performance.

Thus the package is fully interactive, allowing the designer to compare the results of different design algorithms applied to the same problem, with the capability of using one method to improve on the result of another. This capability can be exploited by an experienced designer to lead to the best practical controller for a given system.

The man-machine dialog implemented in MVPACK was designed to meet the needs of a wide range of users, from novices to experts. It is based on a well balanced mixture of command oriented and question-and-answer dialogs. This makes it possible to shift the initiative from the computer to the user, when required, and vice versa.

MVPACK is designed and built as a collection of modular sub-packages to facilitate development, testing, and addition of new modules. It is possible to use existing modules as subroutines in new experimental programs. The benefits are synergistic, since new modules can be developed faster. The package is arranged in a hierarchic structure, Figure 1, with the provision of a help mechanism to guide the user. Each module of a sub-package services one well-defined function with all documentation included in the code. Functions specific to the operating system are localized, so they can be easily adapted to new environments. The package is currently operational in the Dynamic Analysis Laboratory of the Chalk River Nuclear Laboratories (CRNL) on a DEC PDP-11/45 computer, under the IAS 3.1 operating system, and in the Department of Electrical Engineering at the Ecole Polytechnique de Montreal on a PDP-11/60 computer under RSX-11M.

Mathematical Support

MVPACK includes a comprehensive mathematical library to perform real, complex, and polynomial matrix arithmetic.

The variety and the power of the functions and operations implemented in the mathematical library allow MVPACK design and analysis algorithms to be built rapidly with existing blocks [2]. New subroutines can be added to the library, and existing subroutines can be upgraded with new improved numerical methods. Most of the facilities implemented in the library can also be used directly by a control system designer to perform off-line matrix operations before and (or) after the design of a controller. This unique feature proved to be a powerful debugging tool for experimental programs.

The library provides numerically robust routines to perform all the standard algebraic operations on real, complex, and polynomial matrices. It includes an LU factorization module [3,4] extended to process non-square matrices. It finds null spaces and controllability indices, as well as inverse matrices and solutions of simultaneous equations. The library also includes modules to compute the least common multiple and the greatest common divisors of polynomials, using Euclid's algorithm [5].

Data Structure

The data structure has been designed and implemented to retain in MVPACK's modules the efficiency of FORTRAN for matrix processing, with the convenience of an array-processing language.

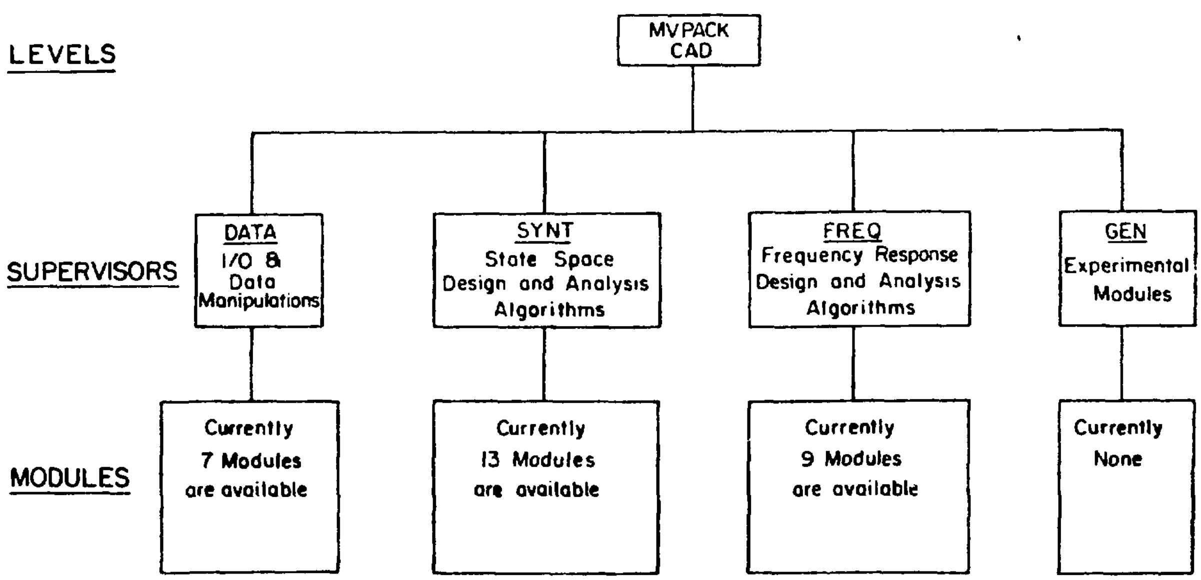

FIGURE 1 MVPACK HIERARCHIC STRUCTURE

It includes dynamically allocated in-core, disk file, and task control structures with built-in interfaces [2,6]. Data structure routines are provided to create, delete, copy, and access the data. They are designed and implemented on the principle of information hiding [7] so the structure is transparent to the application programs.

The application modules are implemented to operate on data grouped under a user-given System Name. The package uses the specified System Name to create/identify a special disk file where all input and output data of a run are dynamically accessed through the data-structure routines.

DESIGN AND ANALYSIS MODULES

The multivariable control problem consists of two parts: design and analysis. Design methods perform a synthesis, based on design parameters provided by the designer, and possibly involving the designer interactively. However, any design involves compromises, or approximations, so it is important to have analysis tools for evaluation of the actual dynamic response of the resulting controller. The modules currently available in MVPACK (see Table 1) provide the user with several design and analysis techniques. The underlying mathematical development of these techniques is described in References 8 to 20. In the following sections, a short description of some of the design modules is given to illustrate the capability of the package.

Regulator Design Modules

The objectives of any process or plant regulators are stability augmentation, sensitivity reduction, and good steady-state tracking. MVPACK provides reliable, powerful tools to meet these objectives. Modules MODE-MODA, REG1-REG2-GRL or DCOM can be used to design a conventional proportional/integral (PI) controller to achieve the regulator requirements.

MODE-MODA

Module MODE synthesizes a modal controller [8,9]. It performs a modal analysis on the open-loop system and prompts for the modes to be shifted and for the inputs to be used. It generates the controller matrices and activates MODA to perform the controller analysis.

REG1-REG2

REG1 synthesizes a proportional feedback matrix to assign max(m,p) poles, where m is the number of inputs, and p is the number of outputs [10]. REG1 computes and displays the open-loop eigenvalues and prompts for assigned values. It then computes the feedback matrix, forms the plant closed-loop A matrix, performs eigenanalysis, and displays the closed-loop poles. If results are not satisfactory, the user can resume REG1, or call one of the other pole-shifting modules. When results are satisfactory, the user can automatically call the integral controller module GRL.

REG2 protects up to min(m,p)-1 poles and computes a proportional feedback matrix to assign max(m,p) poles. It displays open-loop poles and asks for the number of protected poles. The user can select the protected poles, or REG2 will protect an appropriate number of the fastest modes. REG2 prompts for assigned values, calculates the feedback matrix, forms the closed-loop matrix to obtain the closed-loop eigenstructure, then displays the closed-loop poles. If results are not satisfactory, REG2 can be resumed. When results are satisfactory, the user can call the integral controller module GRL.

TABLE 1

ANALYSIS AND DESIGN MODULES OF MVPACK

Module Name	Superviser	Function
CALC	DATA	Interactive real and complex matrix calculator
EDI	DATA	Data Editor
EIG	DATA	Perform eigenanalysis on a matrix
LOA	DATA	Load data from disk file into memory
LUEN	DATA	Perform Luenberger canonical transformation
OUT	DATA	Print selected matrices on the lineprinter
PCAL	DATA	Interactive polynomial and rational matrix calculator
DCOM	SYNT	Design and analysis of a dynamic compensator
GRL	SYNT	Design of an integral controller
MODA-MODE	SYNT	Design and analysis of a modal controller
OPT-OPTA,OSIM	SYNT	Design and analysis of a Kalman filter-optimal controller
PLOT	SYNT	Plot results of open loop, closed-loop simulation
PPCO	SYNT	Perform pole placement with constrained output feedback
RED	SYNT	Perform order reduction of linear model
REG1-REG2	SYNT	Perform pole shifting
RSIM	SYNT	Closed-loop simulation
SIM	SYNT	Simulation of linear model in state-space
BODE	FREQ	Produce Bode plots
COMB	FREQ	Create an overall frequency-response matrix from a block diagram
GSGW	FREQ	Evaluate the frequency response of a transfer function matrix
INA	FREQ	Implement the Inverse Nyquist Array design method
NYQ	FREQ	Generate Nyquist plots
SSGS,SSGW	FREQ	Create a rational transfer function matrix from a state-space model

GRL

The purpose of GRL is to add integral action to the proportional controller computed by REG1 or REG2. It may also be used in connection with any other proportional controller. It prompts for a gain coefficient to shape the overall transient response, and it computes the gain matrix [11] of the integral controller.

DCOM

DCOM extends the design technique implemented in REG1-REG2. It designs a dynamic compensator, with pre-specified poles, that assigns a large number of closed-loop poles [12].

DCOM prompts for the information required to compute the controller matrices. DCOM is highly interactive, so the user can influence the design step-by-step. The final result displayed by DCOM is the closed-loop eigenvalues. If they are not satisfactory, the user can resume DCOM at any of several levels. When results are satisfactory, the user can call RSIM to evaluate the dynamic response of the closed-loop system.

Optimal Control Modules

The general problem of optimal control is to find a control law such that the response of the system minimizes a specified performance index. The performance index is to take into account engineering and economic constraints to ensure safe and efficient operation of the system. In MVPACK, modules OPT-OPTA provide the facility to design an optimal deterministic regulator and steady-state Kalman filter [13,14].

Module OPT designs a linear-quadratic-optimal controller or a Kalman filter, by finding the solution of the appropriate matrix Riccati equation. The duality of the two problems allows both to be solved using the same technique [14]. The method involves the modal solution of the combined state/co-state differential equations [15].

OPTA is a simplified version of OPT to aid in the interactive selection of cost factors. The results of an optimal control design can be simulated using the module OSIM.

Reduction of Linear Systems

For most control problems, the linear model derived from an available plant model is too complex to meet the needs of the controller designer. Order reduction is an analytical procedure that extracts the matrices of the desired low-order model from the given high-order model. In MVPACK, two reduction techniques are implemented in module RED to derive a reduced-order, linear model from a given high-order model [16]. The philosophy of the two techniques [17,18] is to drop the fast, stable modes, while retaining all the unstable modes and the slow modes that lie in the bandwidth of interest for the controller.

Optimization-Based Methods

Sometimes a control system must be designed to meet closed-loop performance specifications as well as practical engineering and physical constraints. Unfortunately, most of the design techniques cannot incorporate these practical constraints right into the design strategy. Thus the designed controller must go through time-consuming, manual tuning with a possible degradation in the overall performance. Optimization-based design approaches have the potential to circumvent this type of problem. The underlying principles of these techniques are:

- define cost functions or performance indices to describe the control system specifications,
- select the physical and practical engineering constraints which must not be violated, and
- derive an algorithm to solve the associated optimization problem and compute the control law.

MVPACK includes such a flexible and powerful technique. The module PPCO implements a design method for pole shifting with constrained output feedback [19]. It designs a structurally constrained controller to assign a specified spectrum of the closed-loop eigenvalues. Constraints may also be put on the controller gains. PPCO is highly interactive, so the user can influence the design step-by-step.

Inverse-Nyquist-Array Method

One of the most important of the multivariable frequency response methods is the Inverse-Nyquist-Array method (INA) of Rosenbrock [20].

The main goal of Rosenbrock's method is to design pre- and post-compensators so that the inverse of the open-loop frequency response matrix is diagonally dominant. In MVPACK, the designer can use module INA to obtain diagonal dominance. Module INA functions as a sub-supervisor driven by user's commands. Once the diagonal dominance has been achieved, conventional compensators can be designed for each of the resulting loops.

MVPACK Operation

In this section, some of the operating features of MVPACK are described to illustrate its flexibility. On the PDP-11/45 minicomputer of the Dynamic Analysis Laboratory at CRNL, MVPACK is entered by the IAS MCR command CAD. CAD prints a header, then prompts for the name of the system to be analyzed. The system name is retained for the duration of a run, so all commands access the same data. CAD then requests a command. The commands recognized by CAD are the names of other supervisors, such as DATA. The user can activate the help mechanism by entering "?".

In the supervisor DATA, the user can set up the initial data through the loading of disk input files or by editing interactively the system matrices. This set of data is automatically inserted in the disk file of the current System Name. Now the user can select the supervisor under which he wants to operate and then choose the module he desires to activate.

The hard copy of a simple run of MVPACK is shown in the Apopendix to illustrate the use of the help mechanism, the loading of an input disk file, and the operation of CALC, the interactive matrix calculator.

APPLICATION

To illustrate the capability of the package, controllers for an evaporator and an aircraft are studied in the following sections.

Study of an Evaporator Control System

Model. The differential equations for an evaporator [21], linearized about a certain operating point, can be written as

$$\dot{x} = Ax + Bu + D \cdot d$$
$$y = Cx \qquad (1)$$

The elements of vectors x, u, d and y are normalized perturbation variables and their definitions in terms of the process variables are given in [21]. The elements of the system matrices A, B, C and D are described in [21]. This model, a fifth-order system with 3 inputs and 3 outputs, has the following open-loop poles

(0, -0.015, -0.038, -0.077, -0.77)

The control objectives are to achieve stability and perfect steady-state tracking, with a non-oscillatory but reasonably fast response.

REG1 and REG2 are used to obtain the proportional controller and GRL is used to introduce the integral action. The design process starts with the activation of REG1 and proceeds through the following steps:

(i) Command is entered in REG1 to assign 3 closed-loop at (-0.04, -0.06, -0.1).

(ii) REG1 computes the feedback matrix K01 (see Table 2) and displays the closed-loop poles

(-0.04, -0.06, -0.072, -0.1, -0.73).

(iii) REG2 receives the command to protect the poles at -0.04 and -0.06 and to shift the remaining poles to (-0.1, -0.2, -0.773).

(iv) REG2 computes the feedback matrix K02 (see Table 2) and displays the resulting closed-loop poles

(-0.04, -0.06, -0.1, -0.2, -0.773).

(v) GRL computes the integral controller matrix K03 (see Table 2) with a gain *coefficient of* 0.025.

(vi) RSIM forms the total feedback matrix

$$K = -\begin{bmatrix} K01+K02 & K03 \\ & \\ I & 0 \end{bmatrix} \qquad (2)$$

and performs the simulation of the closed-loop system.

The results of the simulation, given in Figure 2, show that the system response is stable and sufficiently fast with perfect steady-state tracking.

TABLE 2

FEEDBACK MATRICES COMPUTED BY REG1, REG2, GRL and RSIM

$$K01 = \begin{bmatrix} 0.47 & 0.34 & 9.28\times10^{-3} \\ 4.71 & 3.41 & 9.28\times10^{-2} \\ 0.47 & 0.34 & 9.28\times10^{-4} \end{bmatrix}$$

$$K02 = \begin{bmatrix} -0.17 & 0.76 & 1.11 \\ 1.34 & -5.83 & -8.52 \\ 0.29 & -1.26 & -1.84 \end{bmatrix}$$

$$K03 = \begin{bmatrix} 7.41\times10^{-3} & 2.75\times10^{-2} & 1.56\times10^{-2} \\ 0.15 & -6.03\times10^{-2} & -0.21 \\ 1.90\times10^{-2} & -1.31\times10^{-2} & -2.10\times10^{-2} \end{bmatrix}$$

Optimization-Based Controller for an Aircraft

Model. For a simplified flight control problem, dealing with the inner loop lateral axis, the aircraft dynamics can be described by the differential equations [22]

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) \qquad (3)$$

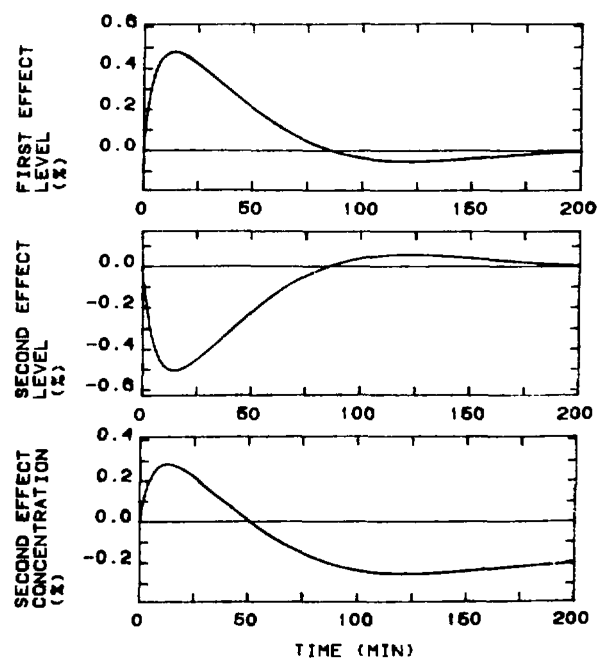

FIGURE 2 EVAPORATOR RESPONSE WITH A PI CONTROLLER TO A SETPOINT REDUCTION OF 20% ON THE SECOND EFFECT CONCENTRATION

where

vector x defines the state variables:

p_s	stability axis roll rate	rad/s
r_s	stability axis yaw rate	rad/s
β	angle of sideslip	rad
δ_a	aileron deflection	rad
δ_r	rudder deflection	rad
θ	bank angle	rad

The input and output vectors are, respectively,

$$u = \begin{bmatrix} \delta_{rc} \\ \delta_{ac} \end{bmatrix} \quad \begin{matrix} \text{rudder command} \\ \text{aileron command} \end{matrix} \qquad y = \begin{bmatrix} p_s \\ r_s \\ \beta \\ \delta_a \\ \delta_r \end{bmatrix}$$

The elements of the system matrices A, B and C are given in [19].

With its poles at $(3.18\times10^{-5}\pm j0.7, -0.2, -0.78, -5.0, -10.0)$, the system is open-loop unstable.

Simulation analysis [19] showed that the system has highly coupled dynamics dominated by the unstable complex modes.

Control Objectives

The control objectives are to achieve stability and fast response with a critical damping factor. It is also desired to reduce significantly the effects of the internal couplings on the dynamics of the aircraft. The poles positioned at $(-0.05, -1.77\pm j1.77, -4, -100, -200)$ were found to satisfy stability, speed and damping requirements. The decoupling of the control actions were based on the following principles:

The rudder command signal should be a function of the sideslip angle, the rudder angle and the yaw rate. To reduce interaction between the control actions, the rudder control should not respond directly to changes in the roll rate and aileron deflection.

The resulting structure for the feedback matrix is

$$K = \begin{bmatrix} 0 & K_{12} & K_{13} & 0 & K_{15} \\ K_{21} & 0 & K_{23} & K_{24} & 0 \end{bmatrix} \quad (4)$$

Controller Designed with Module PPCO

With feedback structure (4), module PPCO was activated with the following input parameters:

Weight factors (20, 0.4, 0.25, 0.25, 0.01, 0.005)

Poles $(-0.05, -1.77\pm j1.77, -4, -100, -200)$

Initial feedback matrix $K = [0]$

Gain limits none

The computed feedback matrix after 600 iterations is

$$K = \begin{bmatrix} 0 & 18.14 & -37.18 & 0 & 9.66 \\ -5.59 & 0 & 4.17 & -9.84 & 0 \end{bmatrix}$$

and the assigned closed-loop eigenvalues are:

-0.05

$-1.77\pm j1.77$

-4.0

-100

-200

showing that exact pole shifting was achieved.

The closed-loop simulation results (see Figures 3 and 4) show that all the design specifications are met. The system is stable and rapidly rejects perturbations with good damping. The dynamic couplings are reduced and the roll rate response is now independent from the slowest mode.

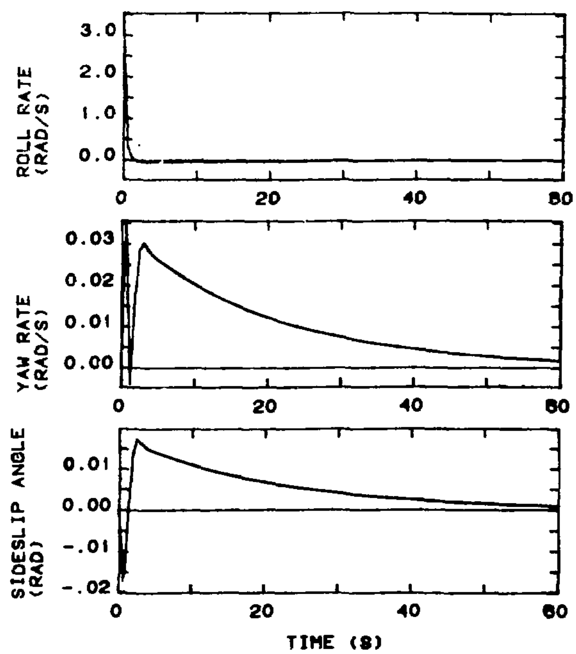

FIGURE 3 AIRCRAFT CLOSED-LOOP RESPONSE TO AN INITIAL ROLL RATE ERROR OF 3.14 RAD/S

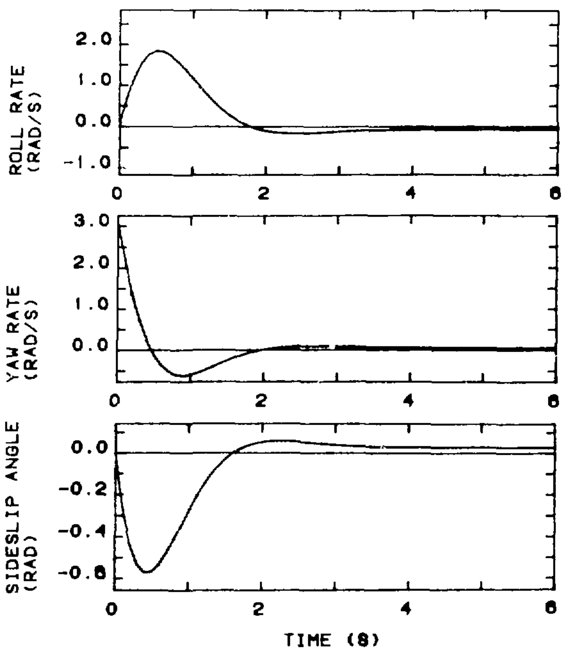

FIGURE 4 AIRCRAFT CLOSED-LOOP RESPONSE TO AN INITIAL YAW RATE ERROR OF 3.14 RAD/S

CONCLUSION

The multivariable, interactive nature of nuclear and other complex process plants is becoming important as unit capacity grows and high-performance control systems are required. The concepts of multivariable control provide an organized and rigorous framework for solution of the problem of dynamic coupling. They lead to techniques which can handle the simultaneous analysis of several plant variables, with the capability to meet system performance specification during the design of the controller.

However, analysis of multivariable systems is complex. Interactive, powerful digital computer programs are required, both to perform arithmetic on real, complex and polynomial matrices, and to execute the complex algorithms used in multivariable techniques.

This report describes MVPACK, a Computer-Aided-Control-System-Design (CACSD) package, developed in the Reactor Control Branch of the Chalk River Nuclear Laboratories. The report reviews the specifications used in the design and implementation of MVPACK. The organization of the database, the mathematical facilities and the structure of the package have been briefly described.

A short description of some of the design modules and some application examples were given to illustrate the capability of the package. The application modules currently available in MVPACK offer a wide spectrum of tools for the design of multivariable control systems. Since MVPACK is built as a modular open-ended package, new design and analysis modules can be added to it as needs arise.

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APPENDIX

```
      CAD
   DAF COMPUTER-AIDED CONTROL-SYSTEM DESIGN PACKAGE
   GIVE SYSTEM NAME>EVAPOR
1* CAD COMMAND>?

   THE FOLLOWING FACILITIES ARE AVAILABLE IN MVPACK

      DATA  -- DATA LOAD, PRINT, AND MANIPULATE
      SYNTH -- SYNTHESIS DESIGN METHODS
      FREQ  -- FREQUENCY RESPONSE DESIGN METHODS
      GEN   -- ACCEPTS ANY COMMAND OR TASK NAME
      BYE   -- EXIT FROM MVPACK
      X     -- RETURN TO NEXT HIGHER LEVEL

   THE BYE AND X COMMANDS MAY BE ENTERED TO ANY SUPERVISOR

2  CAD COMMAND>DATA

   DKINIT -- CREATING NEW DATA FILE FOR SYSTEM EVAPOR
3  DATA COMMAND>?

   THE FOLLOWING FACILITIES ARE AVAILABLE IN THE DATA MODULE

      LOA  -- READ DATA FROM AN INPUT FILE INTO THE DISK
              DATA STRUCTURE
      OUT  -- PRINT ARRAYS ON THE LINE PRINTER IN STANDARD
              ARRAY FORMAT
      EIG  -- PERFORM EIGENANALYSIS ON A MATRIX
      EDI  -- EDIT SYSTEM DATA
      RED  -- ORDER REDUCTION USING MODAL ANALYSIS
      SSGW -- PERFORM STATE SPACE TO FREQUENCY RESP
              CONVERSION
      CALC -- MATRIX CALCULATOR
      SIM  -- SIMULATES MV SYSTEMS IN STANDARD STATE
              SPACE FORM
      PLOT -- PRINTER PLOTS OF SIMULATION MODULE
      BODE -- PRODUCE A BODE PLOT USING SFP
      PCAL -- PERFORM POLYNOMIAL MANIPULATIONS
      SSGS -- PERFORM STATE SPACE TO TRANSFER FUNCTION
              CONVERSION
      GSGW -- PERFORM TRANSFER FUNCTION TO FREQUENCY
              RESPONSE CONVERSION
      TPL  -- TIME RESPONSE PLOTTER FOR THE TEKTRONIX 4663
      LUEN -- DRIVER FOR LUENBERGER CANONICAL FORM SUBROUTINE

   TYPE X TO RETURN TO CAD


4  DATA COMMAND>LOAD

   MVLOAD MODULE
5  GIVE FILENAME>EVAPOR

   SYSTEM NAME SET TO EVAPOR
6  DATA COMMAND>CALC

   INTERACTIVE MATRIX CALCULATOR

7  COMMAND LINE>?
   CALC COMMANDS ARE INV, MUL, INF, COP, TRA, LUF, CON, LNS,
   RNS, SOL, ADD, SUB, SCA, EXT, INS, DIR, SYS, EIG, LUE, EDI, ?
8  ? COMMAND>SSGS
   COMMAND NOT FOUND
9  ? COMMAND>SOL
          SOL A,X,B SOLVES THE EQUATION A*X = B
10 ? COMMAND>EIG
          EIG PERFORMS EIGENANALYSIS
11 ? COMMAND>LUE
          LUE GENERATES THE LUENBERGER CANONICAL FORM
12 ? COMMAND>
13 COMMAND LINE>LUE
   LUENBERGER CANONICAL FORM MODULE
14 GIVE A, B>A*B
15 GIVE NAMES FOR AC, BC, TL, TR>ACC,BCC,TL,TR

   CREATED CANONICAL FORM
   CREATED A-BACK

   INTERACTIVE MATRIX CALCULATOR

16 COMMAND LINE>
17 DATA COMMAND>OUT

   MVOUT MODULE

   DIRECTORY OF SYSTEM EVAPOR
   DSLOAD -- 17 ENTRIES USED OUT OF 198

   A         BCC        Q-CAN01       T-CAN       T-CAN03
   A-BACK    C          Q-CAN02       T-CAN01     TL
   ACC       D          Q-CAN03       T-CAN02     TR
   B         Q-CAN

18 NAMES>A,B,ACC,BCC,A-BACK
   NAMES>
19 DATA COMMAND>SYNT
20 SYNTHESIS COMMAND>?

   SYNTHESIS FACILITIES ARE

      MODE -- DESIGN A MODAL CONTROLLER
      MODA -- ANALYZE A MODAL CONTROLLER
              MODA CAN ANALYZE ANY LINEAR FEEDBACK SYSTEM
      OPTA -- INTERACTIVE ADJUSTMENT OF OPTIMAL COST
      PPCO -- POLE PLACEMENT WITH CONSTRAINED OUTPUT FEEDBACK
      OPT  -- DESIGN OPTIMAL CONTROLLER OR KALMAN FILTER
      SIM  -- SIMULATES MV SYSTEMS IN STANDARD STATE SPACE FORM
      PLOT -- PRINTER PLOTS OF SIMULATION MODUL
      TPL  -- TIME RESPONSE PLOTTER FOR THE TEKTRONIX 4663
      REG1 -- ANALYSIS AND SYNTHESIS OF A MULTIVARIABLE REGULATOR
      REG2 -- CONTINUATION OF REG1
      DCOM -- DESIGN A DYNAMIC COMPENSATOR
      OSIM -- OPTIMAL CONTROLLER AND KALMAN FILTER
      RED  -- ORDER REDUCTION USING MODAL ANALYSIS
      GRL  -- ADD INTEGRAL ACTION TO PROPORTIONAL CONTROLLER
      RSIM -- FORM MATRICES FOR CLOSED LOOP SIMULATION USING SIM

   TYPE X TO RETURN TO CAD

21 SYNTHESIS COMMAND>X
22 CAD COMMAND>BYE

   MVPACK -- EXIT

   PDS>BYE$
```

*The numbered lines indicate steps where user commands are entered.

MVPACK DATA FOR EVAPOR 84-FEB-21 09:37:48

MATRIX A

1	0.000000	-1.100000E-03	-0.125500	0.000000	0.000000
2	0.000000	-7.550000E-02	0.125500	0.000000	0.000000
3	0.000000	-6.000000E-03	-0.774100	0.000000	0.000000
4	0.000000	-1.200000E-03	-0.144800	-1.500000E-02	1.000000E-04
5	0.000000	3.930000E-02	0.144800	0.000000	-3.800000E-02

MATRIX B

1	0.000000	-7.660000E-02	0.000000
2	0.000000	0.000000	0.000000
3	0.216000	0.000000	0.000000
4	0.000000	7.950000E-02	-3.810000E-02
5	0.000000	-4.140000E-02	0.000000

MATRIX ACC

1	0.000000	1.00000	0.000000	0.000000	0.000000
2	-5.826900E-02	-0.776431	1.995930E-03	2.529401E-02	0.000000
3	0.000000	0.000000	0.000000	1.00000	0.000000
4	2.710800E-02	2.13609	-9.285498E-04	-0.111169	0.000000
5	6.330107E-02	1.55935	-9.789269E-04	-2.200552E-02	-1.500000E-02

MATRIX BCC

1	0.000000	0.000000	0.000000
2	1.00000	3.425372E-02	0.000000
3	0.000000	0.000000	0.000000
4	0.000000	1.00000	0.000000
5	0.000000	0.000000	1.00000

MATRIX A-BACK

1	-1.661242E-18	-1.100000E-03	-0.125500	0.000000	8.673617E-18
2	-4.354156E-19	-7.550000E-02	0.125500	0.000000	4.336809E-19
3	-6.205808E-18	-6.000000E-03	-0.774100	0.000000	1.517883E-17
4	2.252879E-18	-1.200000E-03	-0.144800	-1.500000E-02	1.000000E-04
5	-1.635557E-18	3.930000E-02	0.144800	0.000000	-3.800000E-02

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