View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

N90-23049

New Multivariable Capabilities of the INCA Program

Frank H. Bauer, NASA/Goddard Space Flight Center
John P. Downing, NASA/Goddard Space Flight Center
Christopher J. Thorpe, Fairchild Space Company

Abstract

The INteractive Controls Analysis (INCA) program was developed at NASA's Goddard Space Flight Center to provide a user friendly, efficient environment for the design and analysis of control systems, specifically spacecraft control systems. Since its inception, INCA has found extensive use in the design, development, and analysis of control systems for spacecraft, instruments, robotics, and pointing systems. The INCA program was initially developed as a comprehensive classical design analysis tool for small and large order control systems. The latest version of INCA, expected to be released in February of 1990, has been expanded to include the capability to perform multivariable controls analysis and design.

1 Introduction

The INteractive Controls Analysis (INCA) program was developed at NASA's Goddard Space Flight Center (GSFC) as a computer aided control system design tool primarily for use by engineers in the Guidance and Control Branch. The program couples a user friendly interface with excellent, well conditioned computational algorithms to provide control system design analysis engineers tools which are simple to use, quick, and provide accurate results.

Initial development of the INCA program began in 1982 with the first release of program to members of the Guidance and Control Branch in 1983. Since then, INCA has been used extensively to design or analyze control systems for all of Goddard's spacecraft programs. This includes spacecraft attitude control systems, instrument servomechanisms, pointing control systems and robotic control systems. Numerous flight proven designs have been developed or validated using INCA's analytic capabilities. These include the Earth Radiation Budget Satellite (ERBS) spacecraft and the Advanced TIROS-N (ATN) [1] weather satellite series.

In 1985 INCA was delivered to COSMIC [2], NASA's computer program dissemination source, for general distribution. Since then it has been used in industry for spacecraft, instrument and robotic controller design development, university research, classical control system instruction and for use on Department of Defense payloads. Because INCA is a public domain program with source code provided, numerous enhancements have been incorporated in INCA by outside users which are now in the COSMIC version. The most notable enhancement in this category is the describing function analysis capability which was developed by Dr. Bong Wie and Mr. Tobin Anthony of the University of Texas at Austin [3]. This capability was later installed in INCA Version 3.13.

2 *Program Overview*

INCA was developed for use on VAX/VMS computers. The program was written primarily in Pascal; however many of the analysis algorithms are written in FORTRAN, particularly the matrix and multivariable control algorithms which were obtained from the SAMSAN [4] subroutine package. Since INCA was written to perform control system design analysis on very expensive spacecraft and instruments, emphasis was placed on doing the analysis **right the first time.** Thus, the program utilizes algorithms which strive for numerical accuracy and attempt to prevent ill conditioned situations. In some instances these algorithms may be less efficient than others available; however, when expensive spacecraft are at stake, accurate results are of supreme importance.

Figure 1 illustrates the INCA user interface. The INCA executive incorporates a default menu driven command structure with a VAX/VMS-type command option. These executive commands can be used to access the graphic and editor modes, query the help library, retrieve data from input files, and create and manipulate transfer functions and matrices. All commands invoked in INCA are parsed, interpreted, and checked for errors. The parsing capability allows the user to either type the full command, or simply use one or two letters in the command. Also, VAX DCL commands can be invoked without leaving the INCA environment.

Input data can include user defined transfer functions, gains, matrices, or specially generated INCA command sequences.

Transfer functions can be developed using the function editor, as alphanumeric input data from other programs, or by using FORTRAN-like arithmetic expressions. For example, a closed loop system can be computed as follows:

```
INCA> G = 1/I/s^2
INCA> H = KR * s +KP
INCA> CLTF = G / (1 + G*H)
```

The results of each INCA session are documented in an output file with the project name. Transfer functions and matrices are stored in either a binary format (the default) or alphanumeric format. INCA generated plots are displayed on local graphics terminals and can be copied using standard hard copy capabilities. Graphics can be viewed on a wide variety of color and monochrome terminals including Tektronix color and monochrome graphics terminals, DEC VT terminals and some Macintosh and IBM PC terminal emulators. Graphic output devices include, but are not limited to, the Tektronix color graphics printers, DEC Laser printers and local terminal hardcopy devices.

3 *Classical Design Analysis Tools*

Using INCA's command menu, the controls engineer can quickly generate system models. These models are then stored in transfer function form for Single-Input-Single Output (SISO) systems or in matrix form for Multi-Input-Multi-Output (MIMO) systems. INCA provides the capability to analyze continuous systems, sample data systems and hybrid (continuous/sample data) systems. In addition, systems with computational delays or

transport lags can also be analyzed via the modified z-transform. The resultant linear models can then be manipulated to modify the design or can be used to determine system stability, parameter robustness or control system performance. Standard filter and control law templates have also been included to expedite system design.

INCA provides a comprehensive host of standard classical controls analysis techniques including Root Locus, Frequency Response (Bode, Nichols, Nyquist) and Linear Time Response capabilities. In addition, frequency response analyses of nonlinear systems can be performed using the describing function method [3]. Analysis results are presented as multi-colored plots with a full range of simple plot manipulation commands. Plot zooming and multiple plot windows capabilities are available as well as simple plot documentation capabilities. Analysis results can also be presented in tabular form. Figures 2-4 represent some of the design analysis plots which can be generated by INCA users.

4 Multivariable Capabilities

The multivariable capabilities incorporated in latest version of INCA, version 4.0, will serve as the foundation for all future multivariable enhancements to the program. The primary goal of version 4.0 was to incorporate all those capabilities necessary to perform rudimentary MIMO analyses. Additional MIMO enhancements will follow later.

First and foremost, a user-friendly matrix input/output environment was developed. This includes:

- Line & full screen editing
- Matrix parsing, row & column concatenation, and submatrices
- Matrix development capabilities such as identity matrices and diagonal matrices from vectors, and
- Input/output from various ASCII and binary files.

INCA will accept matrices with real, complex, and string or so-called "dynamic" elements. The dynamic matrices, similar to the dynamic transfer functions in INCA, work like a spreadsheet. As a variable such as an inertia changes, the matrix is recomputed to incorporate this change. INCA's MIMO extension is unique in that it accepts matrices of 0th order (with just an information header), 1st order (vectors), 2nd order (standard mxn matrices), 3rd order (mxnxo matrices) and beyond.

Matrix arithmetic and linear algebra utilities have been installed in the program. The matrix math operations include addition, subtraction, multiplication, matrix inverse, matrix transpose and exponentiation. As with transfer functions, these operations can be performed in symbolic form, e.g.:

```
INCA> C= ((A*B)^- + D))^3
INCA> E= D'
```

where ⁻ and ' represent matrix inversion and matrix transpose operations respectively and the other operands should be obvious to BASIC or FORTRAN computer program users. Standard linear algebra routines are also available to the user including Eigenvalue/Eigenvector computations, solving the determinant of a matrix, trace computations and singular value decomposition calculations.

Controls specific MIMO capabilities include transfer function to state variable form transformations, state variable to transfer function matrix computations, linear quadratic regulator and linear quadratic estimator design and a structural finite element model reduction capability.

5 Structural Mode Significance

The structural mode significance module embedded in INCA was developed to provide a user-friendly model order reduction capability. This module was designed to expedite the model order reduction process from the initial step of loading the model information into the INCA data base through to the final step of automatically generating reduced order flexible body plant transfer matrices.

Structural dynamic models, such as that provided by the NASA Structural Analysis program, NASTRAN, [5] can be described in the following form:

$$M\ddot{x} + D\dot{x} + Kx = F \qquad (1)$$

where M, D, and K represent the system mass, damping and stiffness matrices respectively, x represents the flexible system's translation and rotation degrees of freedom, and the external forces and torques which act on the body are defined as F. Using the modal coordinate transformation:

$$x = \phi q \qquad (2)$$

where ϕ represents the mass normalized eigenvector matrix computed via programs such as NASTRAN, then the system finite element model of equation (1) can be expressed as:

$$\ddot{q} + C\dot{q} + \lambda q = \phi^T F \qquad (3)$$

where λ is a diagonal matrix of system eigenvalues (the square of the modal frequencies), C is a diagonal matrix representing the modal damping and ϕ^T is the transpose of the mass normalized eigenvector matrix defined in (2). The mode significance analysis in INCA relies on the system modeling and modal coordinate definitions described in equations 1-3. Data input to INCA includes the mass normalized eigenvector matrix, ϕ, and the system eigenvalues, λ, obtained through NASTRAN, the user defined modal damping matrix, C, and the locations of the force/torque and sensor locations defined in x.

Once the system model parameters are defined in INCA, a number of model reduction techniques are available to the user. These include simple gain techniques such as modal gain criteria, [6], and frequency weighted significance criteria such as the Peak

Amplitude [7] and Gregory's model reduction criteria [7] [8]. Moreover, user-defined frequency weighting criteria, such as sensor dynamics frequency shaping or control bandwidth shaping, can be used to augment the criteria described above.

Mode significance analysis results can be displayed through the use of two and three dimensional color plots (figure 5) or by viewing the results in tabular form. These results can then be used to automatically or manually select the modes to keep in the model. Special commands have also been included to automatically generate the plant transfer matrices from the reduced order model.

6 Future Plans

The multivariable controls capability described in this paper will be incorporated in Version 4.0 of INCA which is expected to be released to COSMIC in February of 1990. INCA enhancements planned beyond Version 4.0 include extending the multivariable controls and mode significance capabilities, transfer function identification from frequency response plots, and an interactive compensator synthesis capability. In addition, a PC and MacIntosh derivative of INCA is currently under development at NASA Goddard called ASTEC (Analysis and Simulation Tools for Engineering Controls). ASTEC, described in detail in reference 9, is planned for release to COSMIC in late 1990.

7 Conclusions

The INteractive Controls Analysis (INCA) program couples a user friendly interface with excellent, well conditioned computational algorithms to provide control system design analysis engineers tools which are simple to use, quick, and provide accurate results. The latest version of the program, expected to be released in early 1990, will extend INCA from it present status as comprehensive classical controls tool to one which includes multivariable controls analysis and structural model order reduction capabilities. These enhancements promise to make INCA and it's PC derivative called ASTEC the premier controls analysis tools into the 1990's and beyond.

References

1. Bauer, F. H. and Downing, J. P., "Control System Design and Analysis using the INteractive Controls Analysis (INCA) Program", AIAA Guidance, Navigation and Control Conference Paper 87-2517, 1987.

2. Bauer, F. H. and Downing, J. P., "INteractive Controls Analysis (INCA) Version 2.0", Program Number GSC-12998, COSMIC, University of Georgia, Athens GA., 1985, updated to Version 3.13, 1989.

3. Anthony, T., Wie, B., and Carroll, S., "Pulse-Modulated Controller Synthesis for a Flexible Spacecraft", AIAA Paper No. 89-3433, 1989.

4. Frisch, H. P., and Bauer, F. H., "Modern Numerical Methods for Classical Sampled Systems Analysis (SAMSAN Version 2) User's Guide", Program Number GSC-12827, COSMIC, University of Georgia, Athens, GA., 1984.

5. "The NASTRAN Theoretical Manual", NASA SP-221-(06), COSMIC, University of Georgia, Athens, GA., January 1981.

6. McGlew, D. E., "MODESIG, a Computer Program to Determine the Significant Flexible Modes", GSFC Guidance and Control Branch Report No. 324, November 1982.

7. Class, B. F., Bauer, F. H., Strohbehn, K., and Welch, R. V., "Space Infrared Telescope Facility/Multimission Modular Spacecraft Attitude Control System Conceptual Design", AAS Paper No. 86-031, AAS Guidance and Control Conference, 1986

8. C. Z. Gregory, "Reduction of Large Flexible Spacecraft Models Using Internal Balancing Theory," J. Guidance and Control, Vol. 7, No. 6, Nov-Dec 1984, pp. 725-732.

9. Downing, J. P., Bauer, F. H., and Thorpe, C. J., "ASTEC--Controls Analysis for Personal Computers", 3rd Annual Conference on Aerospace Computational Control, Oxnard CA, August 28-30, 1989.

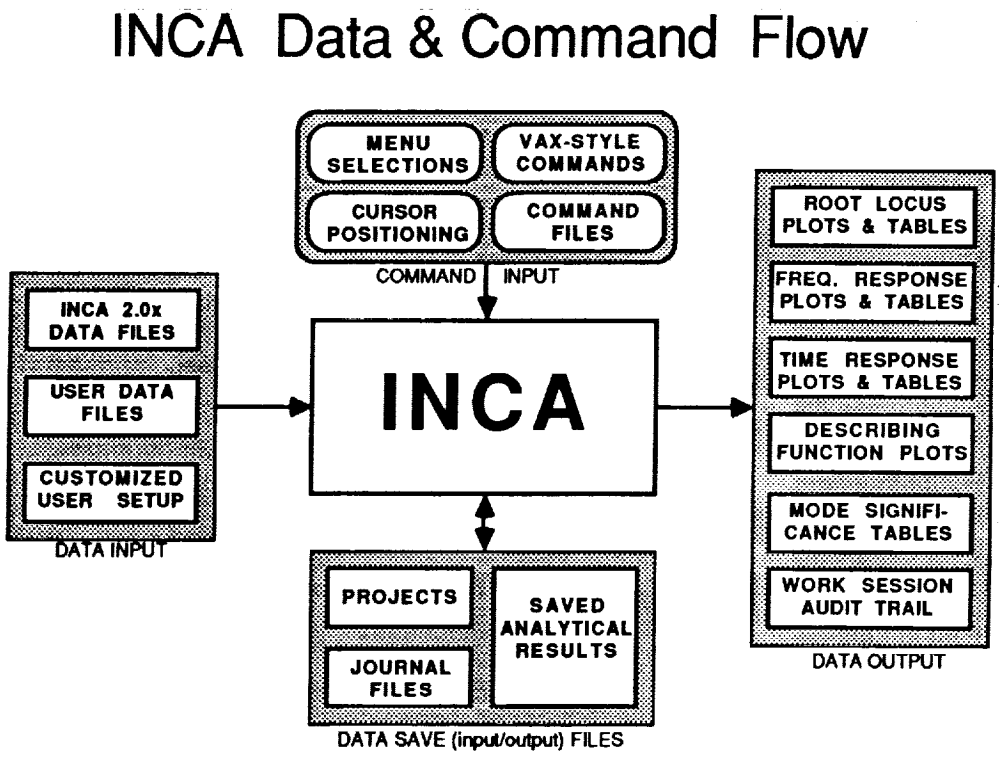

Figure 1

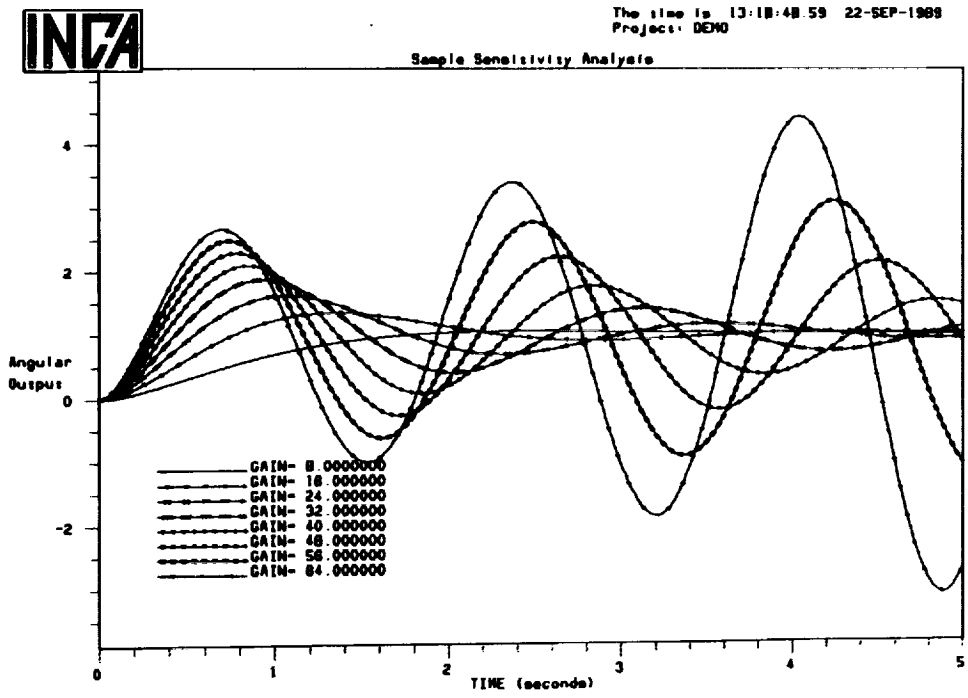

Figure 2

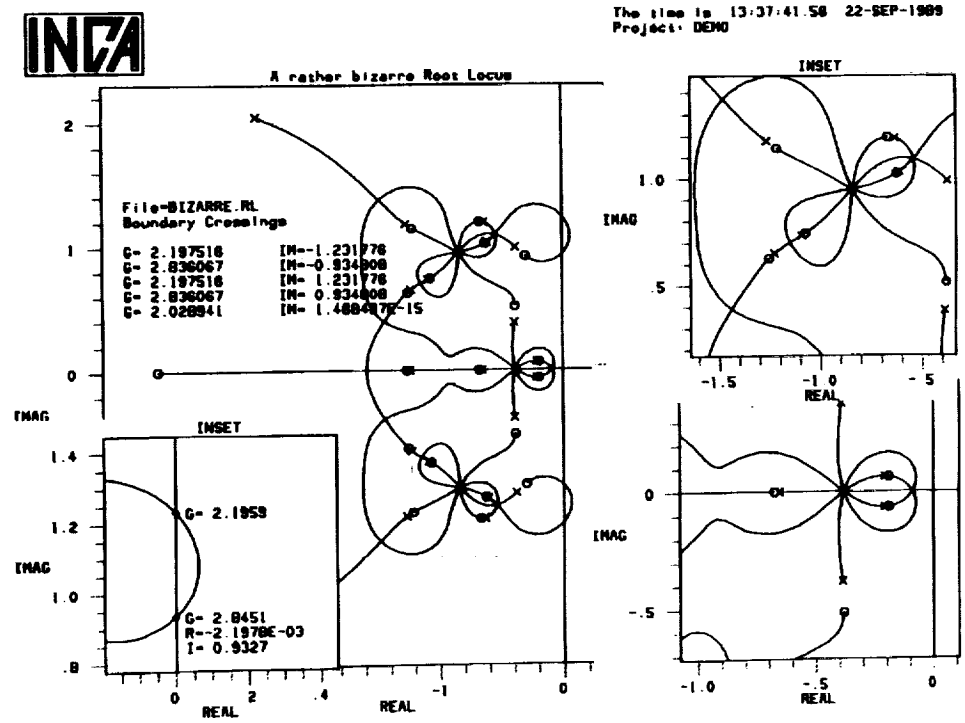

Figure 3

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

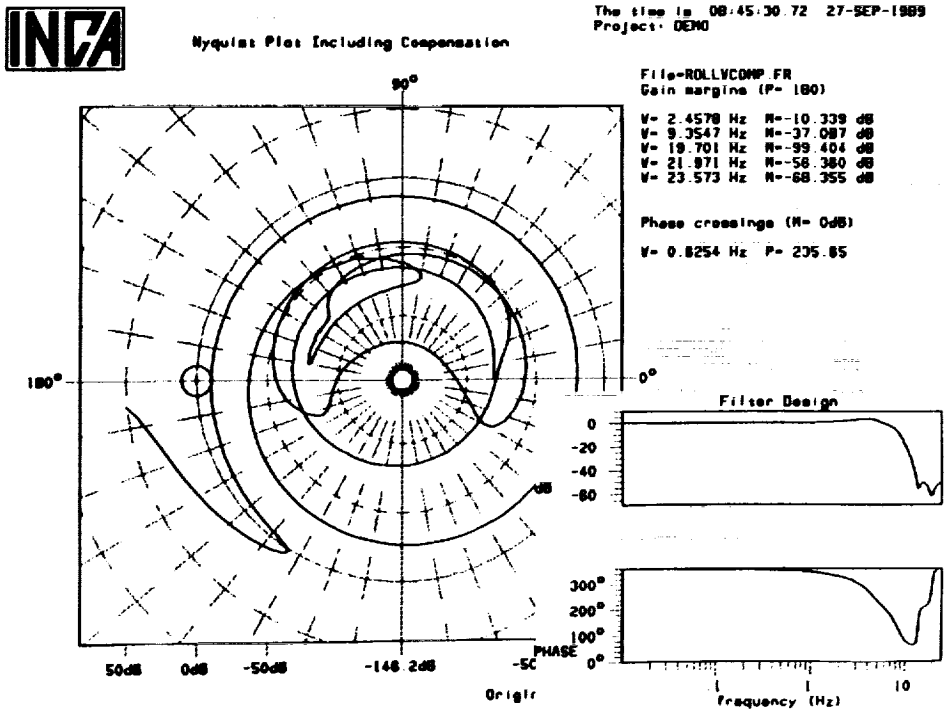

Figure 4

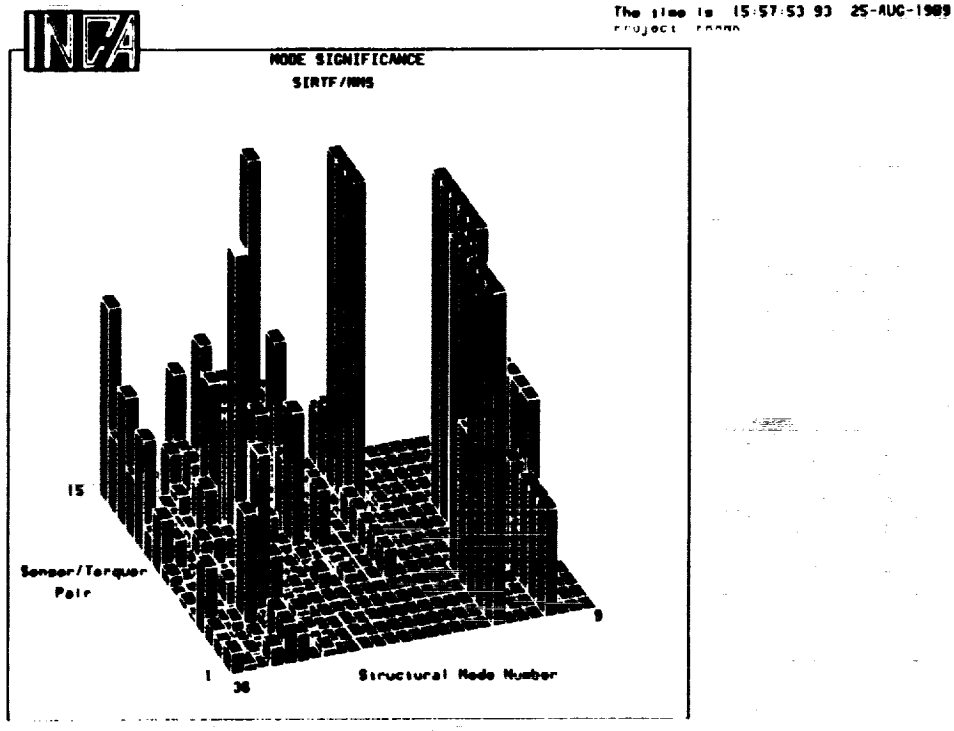

Figure 5